JOURNAL OF

The British Institution of Radio Engineers

(FOUNDED IN 1925 – INCORPORATED IN 1932)

"To promote the general advancement of and to facilitate the exchange of information and ideas on Radio Science."

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THE 21st ANNIVERSARY OF THE INSTITUTION

By a happy coincidence, this year of peace also marks the 21st year of the Institution. For members there is, therefore, double cause for celebration and the General Council have decided that the 21st Anniversary of the Institution shall be appropriately commemorated on Thursday, October 31st, 1946, by the holding of a dinner at the Savoy Hotel, London. Whilst present conditions will make it quite impossible to accommodate every member at this dinner, the Officers and Council nevertheless look forward to welcoming several hundred members.

Further details will be sent to members within the next few months, but meanwhile it is appropriate to recall that the founding of the British Institution of Radio Engineers was very materially helped by the development and use of radio science during the previous (1914-1918) Great War. Additional encouragement for the enterprise of establishing a new British Institution was also derived from the success which had attended the American Institute of Radio Engineers, formed in 1912—a little less than twenty-one years after Marconi came to England and lodged his application for the patent for a system of telegraphy using Hertzian waves. The British Institution of Radio Engineers was not, however, the first Institution of its kind in the British Commonwealth and Empire, for the Institution of Radio Engineers of Australia was founded in 1921 and its established position to-day may be judged by the fact that H.R.H. the Duke of Gloucester, K.G., recently became a Patron of that Institution.*

It was not until May, 1925, however, that there appeared in the various wireless journals of that time first comments upon the intended establishment of the British Institution of Radio Engineers—in those first days the title was not certain and the founders were referred to as members of the British Institute of Radio Engineers and, subsequently, of the Institution of Wireless Engineers. The summer of that year saw the development of the plan for forming the Institution and by the autumn the Institution was well launched ; indeed, the first recorded members' meeting actually took place on October 31st, 1925.

Since then, the Brit. I.R.E. has well established itself with a world-wide membership and has overcome all the difficulties created by an international war without losing any of the ideals which promoted the Herculean efforts of its original founders ; indeed the membership and status is higher to-day than ever before in its history.

We may now confidently look forward to even greater achievements, not only in the growth of membership, but in the fulfilment of the objects of the Institution which may be briefly summarised as advancing the science and practice of radio technique, in which, obviously, is included electronics.

Definition of the Objects

In the last twenty-one years, tremendous strides have not only been made in radio technique, but also in the application of the art ; it is, perhaps, natural that laymen should still regard radio as a means of communication, for it is only 25 years ago that radio telegraphy, as it was then called, excited popular imagination. How progress has been made may best be judged by reading a petition lodged in December, 1921, with the then Postmaster-General, the Rt. Hon. F. G. Kellaway, M.P., by the Wireless Society of London.* This

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* Members will be pleased to note in this Journal (page 18) the first paper reprinted from the Proceedings of the Australian Institution, who enjoy reciprocal arrangements with the Brit. I.R.E.

The British Institution of Radio Engineers

(FOUNDED IN 1925 - INCORPORATED IN 1932)

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World Radio History

Society had a membership of 395 and its Honorary Secretary was Mr. Leslie McMichael (now President of the Institution).

The petitioners stated that their requirements "... have led to the establishment of enormous factories for the manufacture of wireless instruments and apparatus ..." and "There is also the advantage in the case of any future wars of the existence of a number of persons skilled in wireless." In point of fact, the next war actually necessitated the employment of some hundreds of thousands of persons in the manufacture or use of radio equipment!

Radio principles have also been used in improving and developing other industries and arts and the term "electronics" is now used to describe the wider use of the radio valve and kindred devices; it is radio technique at work in new ways and in widely diverse fields and it is opportune to note the main object for which the Institution is established, viz.:—

> The advancement of the science and practice of radio engineering and to afford the means for facilitating the acquisition and preservation of the knowledge pertaining to the profession of a radio engineer and to promote the general advancement of and to facilitate the exchange of information and ideas on radio science and engineering including the theory science practice and engineering of electronics and all kindred subjects and their applications.

Radio Convention

Apart from the *Journal*, the meetings of the Institution are the main means by which knowledge may be disseminated and ideas exchanged. It was hoped that, during this year, the Institution would be able to mark its anniversary celebrations by convening an International Conference of radio engineers. Indeed, in the 1942/3 Annual Report, it was stated that such a Convention would be held within twelve months of the cessation of hostilities against Japan. The impossibility of securing appropriate accommodation, the difficulty of travel, etc., have, however, made it quite impossible to hold a convention during 1946. The Council have, therefore, decided that the Convention shall be held in April or May, 1947; the probable venue is Bournemouth and it is hoped to welcome many overseas members and visitors both at the Dinner in October next and at the 1947 Convention.

Fuller details will be published in succeeding issues of the *Journal*, but meanwhile, the Programme and Papers Committee of the Institution would be pleased to receive suggestions and offers of papers, discussions and similar Convention arrangements.

Overseas members of the Institution who intend visiting England about the time of the dinner or the Convention are urged to communicate with the Secretary as soon as possible their intention to be present.

The President-elect

Council's nomination of a President-elect for 1946/7 is a tribute to an outstanding personality of our victorious Forces, as well as the election of the senior Vice-President of the Institution, Admiral the Lord Louis Mountbatten.

Elected a Member of the Institution in March, 1935, Admiral the Lord Louis Mountbatten completed his training at the Naval Signals School in 1925 (the year in which the Institution was founded). It is noteworthy that in that year he took first place in the Long Signals Officers' Course and was awarded the Jackson-Everett Prize. For the next nine years he served as a Signals Officer afloat and then became senior instructor of the Signals School, Portsmouth.

In this latter appointment, Admiral Mountbatten was responsible for the writing of the first Admiralty Handbook on Wireless Telegraphy—now a standard work. Earlier he had produced many inventions and improvements in signals gear, and after his appointment at the Signals School, Admiral Mountbatten was appointed Fleet Wireless Officer of the Mediterranean Fleet.

The work of our President-elect during the past few years is well known, but he has at all times maintained a close interest in the work of the Institution. Evidence of his particular interest in the training and education of the radio engineer is exemplified by the establishment of the "Mountbatten Medal," awarded to the most outstanding candidate of the three Services successful in the Institution's Graduateship Examination.

The membership will look forward to the induction of Admiral Mountbatten as President of the Institution on October 31st next.

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* The President was recently presented with a facsimile of the original petition to the Radio Society of Great Britain.

UNIFICATION OF LINEAR NETWORK THEORY *

by

J. D. Weston, B.Sc., B.Sc.(Eng.).

SUMMARY

The concern of this paper is not so much to present new concepts as to achieve a unification of old ones in a consistent scheme.

The theory of linear networks is developed from its fundamental laws in the light of the Principle of Duality. The usefulness of this principle, both in clarifying ideas and in shortening calculations, does not seem to have been adequately appreciated hitherto, and the paper is largely an attempt to emphasise its value. Well-known theorems are considered in relation to the general principle, and some apparently new theorems are proved.

At the end of the paper a brief discussion is given of duality in regard to the electromagnetic field.

Preliminaries

Mathematical physics has many formal characteristics in common with geometry, which is usually regarded as a branch of pure mathematics. They are both deductive sciences, proceeding in each case from a set of axioms by processes which belong purely to logic. In the case of geometry, the axioms are merely hypotheses, and may be quite arbitrary. If the axioms of a particular geometry agree with experience then that geometry may be regarded as applied mathematics. In theoretical physics, however, the axioms are empirical laws, expressed in mathematical form, that is to say, they are generalisations from experience, obtained by a process of induction. To build a consistent structure on the basis of these axioms is the concern of the mathematician, and as such he is not interested in the physical status of his axioms.

It is the aim of the mathematical analyst to reduce as far as possible the number of axioms necessary to sustain his subject. It is thus his function to remove redundant members from the structure of mathematical knowledge. The theoretical physicist has a similar aim. He seeks constantly a unifying principle in nature—a principle which embraces all natural phenomena as aspects of one conceptual whole. In many respects, therefore, his enquiries follow a parallel course to those of the pure mathematician. It is, then, to be expected that he should often find a principle which dominates a branch of pure mathematics also dominating a branch of theoretical physics. One of these is the Principle of Duality—one of the most elegant and fruitful concepts in the whole of mathematics. It is shown in this paper that a duality is discernible in the axioms upon which the theory of electrical networks is founded, *and that it therefore extends, with complete universality, to all the ramifications of that theory.*

The fact that such a duality exists has been pointed out many years ago, and some use has been made of it[1, 2, 3, 4, 5]. However, its full value does not seem to have been appreciated hitherto, and those text-books on network theory which mention it at all do so near the end rather than at the beginning. Accordingly, it is thought worth while to give a general discussion of the principles of network theory in the light of this concept, in the hope that it will form a useful contribution to the unification of the subject. In the course of this discussion, some theorems emerge which do not appear to have been generally known before. It is important to notice that, although this paper treats exclusively electrical networks, it will be apparent that the same general principles apply to any dynamical theory, the axioms of which can be formulated in an analogous way.

Projective geometry is concerned with properties of conjunction amongst the geometrical elements, points, lines and planes. Examination of its axioms reveals that they fall into correlative pairs. Either member of each pair can be converted into the other by interchanging certain words. Correlative words for three dimensions, are "point" and "plane," "join" and "meet," "concurrent" and "coplanar." "Line" and "collinear" are self-corresponding terms. In virtue of this correspondence it is possible to halve the number of axioms required, provided we add to them the Principle of Duality.

Since the axioms fall into pairs in this way, so do all the consequences of the axioms. Every theorem has a correlative which can be inferred immediately by the Principle of Duality once the first theorem has been proved. Thus a theorem about points and lines in space has a correlative involving planes and lines. It is necessary to prove only one of the theorems by the usual methods.

The Axioms of Network Theory

In the discussion of electrical networks which we now undertake, phenomena of space propagation and radiation are neglected. The justification of this involves two assumptions :—

(1) That the currents and potentials are either "steady" or "slowly varying," that is, the free-space wavelengths of oscillations are very long in comparison with the physical dimensions of the networks considered.

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* MS. received June, 1945.

(2) That the circuit parameters are "lumped," that is, not distributed as in transmission lines, etc. (i.e., the networks considered are "*finite*").

It is also assumed throughout that the networks are "stationary," that is, that all the circuit parameters are independent of time.

With this understanding, we may assert that the theory of linear* bilateral electrical networks is based entirely upon the following six axioms, which are true at every instant of time :—

(1a) *The total current flowing to (or from) a junction in a network is zero* :

$$\Sigma i = 0.$$

(1b) *The total fall of potential in either direction round a mesh in a network is zero* :

$$\Sigma v = 0.$$

(2a) *The current in a resistive element of a network is proportional to the fall of potential across it* :

$$i = gv.$$

(2b) *The fall of potential across a resistive element of a network is proportional to the current in it* :

$$v = ri.$$

(3a) *The current in a capacitative element of a network is proportional to the time rate of change of the fall of potential across it* :

$$i = c\dot{v}.$$

(3b) *The fall of potential across an inductive element of a network is proportional to the time rate of change of the current in it* :

$$v = l\dot{i}.$$

It is evident at once that these axioms fall into three correlative pairs. Corresponding components of a network are "junction" and "mesh." "Branch" and "element" are self-corresponding. These components are thus analagous to the elements of three-dimensional projective geometry. Other correspondences are "current to a junction" and "fall of potential round a mesh," "conductance" and "resistance," "capacitance" and "inductance." Differentiation with regard to time is a self-corresponding operation.

The first two axioms stated above are Kirchhoff's laws. They are not independent, since both can be deduced, for steady currents, from Coulomb's law of inverse squares,† but since this is a concept foreign to network theory, they are best regarded as fundamental.

The second two axioms are equivalent formulations of Ohm's law. To give the two forms the distinction of separate axioms may seem highly artificial, but it amounts to providing a convenient means of defining "conductance" and its reciprocal, "resistance." Two statements are obviously necessary to define two quantities, even though they are simply related to each other (if preferred, Ohm's law can be regarded as corresponding to itself, since it refers to a property of self-corresponding components. However, the distinction we have made does not seem essentially different from the distinction between "collinearity" and "concurrence" when we consider that this is unnecessary for many purposes if we use the single word "syzygy"). There is, of course, a theory of metallic conduction which explains Ohm's law, but as far as network theory is concerned, it may be regarded as an empirical law *sui generis.*

The third two axioms serve to define capacitance and inductance: (3a) follows from Coulomb's inverse square law in electrostatics and (3b) from Neumann's law of electromagnetic induction. We can always take account of the effects of mutual inductance by regarding it as equivalent to self-inductance common to two or more meshes (or branches) together with a compensating negative inductance in each mesh.*

By means of the last pair of axioms, we can generalise Ohm's law so as to apply to "steady-state" alternating currents, and thence, by means of the operational calculus, to currents of any waveform. We then introduce the correlative terms "susceptance" and "reactance," which have the nature of imaginary conductance and resistance respectively, and the correlative complex quantities "admittance" and "impedance."

Generalisation of Kirchhoff's Laws

Kirchhoff's laws can be generalised as follows :—

We imagine a network to be represented by a plane diagram, and we draw any closed curve intersecting any number of branches of the network (Fig. 1*a*). Then the generalised laws are :—

(1c) *The total current flowing across the curve into (or out from) the region bounded by it is zero at every instant* :

$$\Sigma i = 0.$$

(1d) *The total fall of potential round the curve in either direction is zero at every instant* :

$$\Sigma v = 0.$$

The first of these statements may be proved by induction. Let it be true for a curve, *c*, enclosing *n* junctions. Now draw a second curve, *d*, surrounding the first curve and an additional junction A (Fig. 1*b*). Then the currents crossing *d* are those crossing *c*

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* The word "linear" has two meanings, and both are intended here. The flow of current in each branch of a network is one-dimensional, and the parameters, r, g, c, and l, which appear in the fundamental laws are independent of current and p.d., so that the network equations are of the first degree.

† If the first of Kirchhoff's laws were not true, it would be possible for electric charge to accumulate at a point. But a finite charge at a point would give rise to an infinite repulsive force and consequent disruption of the charge. Hence it cannot exist. The second law follows because the inverse square law is derivable from a single-valued potential, which we assume to be propagated with an infinite velocity through the space between the elements.

* This introduces an additional junction to the network.

together with those flowing to A, minus currents which flow directly between c and A. That is

$$\Sigma i_d = \Sigma i_c - \Sigma i_{Ac} + \Sigma i_A - \Sigma i_{cA}.$$

But $i_{Ac} = -i_{cA}$, so these currents cancel in pairs. Hence, since $\Sigma i_c = 0$ by hypothesis and $\Sigma i_A = 0$ by Kirchhoff's first law, we have $\Sigma i_d = 0$. Thus, if the statement is true for a curve enclosing n junctions, it is true for a curve enclosing $(n + 1)$ junctions, and, therefore, for any closed curve in any network, since it is true for $n = 1$.

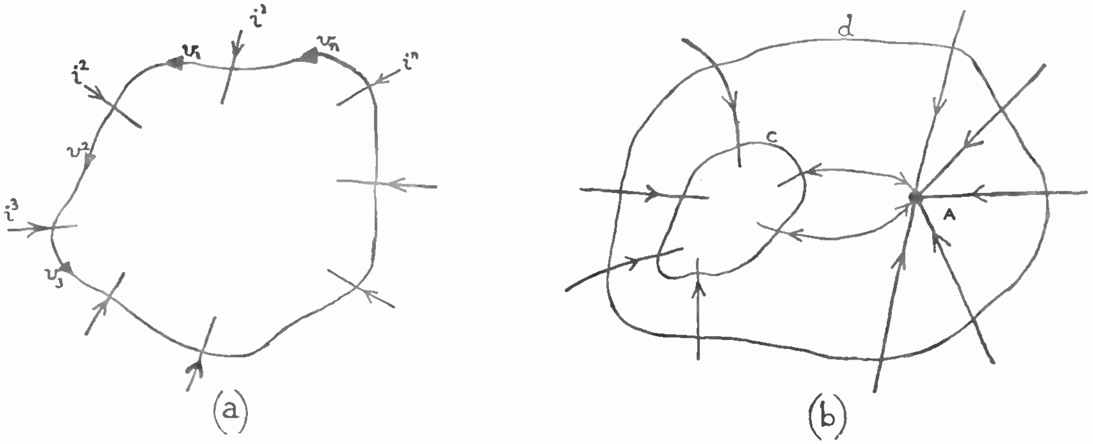

Fig. 1.—*Illustrating Generalisation of Kirchhoff's Laws.*

The second generalisation is correlative to the first. It may be proved independently by replacing the original closed curve by an equivalent path having the same points of intersection but following the lines of the network diagram. Then each partial element enclosed by the original curve is traversed twice, once in each direction, and the remainder of the path consists of a mesh within the network. Thus, by Kirchhoff's second law, the total fall of potential is zero.

It may be noted that Kirchhoff's laws and the generalisations given above are true whether or not there exist discontinuities of current or potential due to the presence of generators in a network (a "branch" of a network may contain a generator but an "element," by definition, cannot).

Generators

An electrical network may be energised by one or more sources of constant potential difference (electromotive force), or by one or more sources of constant current ("constant" meaning, of course, independent of the load, not necessarily independent of time*). These types of source are correlative to each other. There may, of course, be sources of both types present simultaneously in a network. In this case, by the Principle of Superposition for linear systems, the effects of each may be calculated separately and the results added together.

The term "electromotive force" is convenient when we wish to distinguish between the fall of potential due to the flow of current in an impedance and the difference of potential which exists between the terminals of a generator when there is no current flowing through it. There is no correlative term in common use, so it is suggested that the word *flow* be used to denote the current produced by a "constant-current generator." Just as the e.m.f. of a constant-voltage generator is its open-circuit potential difference, so the flow of a constant-current generator is its short-circuit current.

It is frequently useful, especially in connection with Thevenin's theorem, to regard a generator as a source of e.m.f. in series with an impedance—the internal impedance of the generator (Fig. 2*a*). The correlative (and equivalent) concept is that of a source of flow in parallel with an admittance (Fig. 2*b*). This representation is convenient when Norton's theorem is used, and especially in cases where the generator is a pentode valve, the internal a.c. admittance of which is often small enough to be neglected.

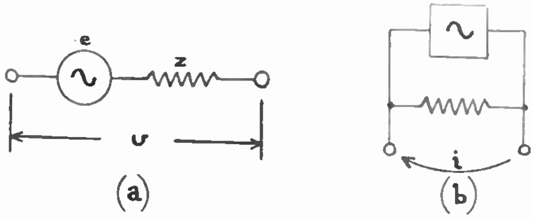

Fig. 2.—*Correlative Representations of a Generator (Equivalent if e = fz and f = ey).*

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* The word "static" can be used if we wish to indicate independence of time specifically.

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A general term to include e.m.f. and flow would be "*source strength.*" A source of negative srength would then be a "*sink.*" A sink occurs in an electric motor, where the back e.m.f. is proportional to the speed at which the machine is running, and also in a gas-discharge lamp, where the back e.m.f. is the extinction voltage. A less satisfactory example is a battery which is being charged. In this case, a reversal of the connections changes the sink to a source.

A network is "*active*" if it contains sources or sinks. It is "*passive*" if it contains neither. A negative resistance is not the same thing as a generator, in the sense in which the word is used here, although it is capable of supplying energy.

Some Illustrations of the Principle of Duality

Before proceeding further with this discussion, it may be as well to give a list of correlative and self-corresponding terms used in general network theory. This is done in the following tables :—

Table of Correlative Terms

Junction (Point, Star, Node)	Mesh (Loop, Ring, Contour)
Parallel (Shunt)	Series
π	T
Short-circuit	Open-circuit
Conductor	Resistor (insulator)
Flow (f, F)	Electromotive force (e, E)
Current (i, I)	Fall of potential (p.d.) (v, V)
Electrokinetic	Electrostatic
Conductance (g, G)	Resistance (r, R)
Capacitance (c, C)	Inductance (l, L or m, M)
Elastance (s, S)	Levitance† (γ, Γ)
Susceptance (b, B)	Reactance (x, X)
Admittance (y, Y)	Impedance (z, Z)
Resonance	Anti-resonance
*Magnetic charge** (in an inductance $= li = p$ (P)	Electric charge (in a condenser) $= cv = q$ (Q)
Contravariant	Covariant

Table of Self-Corresponding Terms

Branch
Element
Generator
Rate of change
Frequency
Energy
Power
Load
Mutual
Characteristic (Iterative)
Propagation (or Transfer) Constant
Conjugate (as applied to branches of a network and as applied to complex numbers)
Common

In order to dualise a network theorem, we replace each word (or symbol) which occurs in its enunciation by the correlative word (or symbol). Thus Thevenin's theorem and Norton's theorem are correlative to each other, and it is unnecessary to prove each separately (it has been stated[6] that Thevenin's theorem is a consequence of the Principle of Superposition, but the general principle need not be evoked, and the theorem is, in fact, true for non-linear impedances).

The Compensation theorem also has a correlative which may be stated as follows :—*Any admittance in a network may be replaced by a constant-current generator, of zero internal admittance, whose generated flow is equal at every instant to the current produced in the replaced admittance by the fall of potential across it.* This is a simple but very useful tool. It applies to both linear and non-linear impedances.

Sometimes the correlative of a theorem amounts merely to a restatement, so that nothing new emerges. This is the case with, for example, the theorem (due originally to Stokes) concerning the matching of a load to a generator to obtain maximum power output (if two elements have conjugate impedances, they also have conjugate admittances). We must get the same condition in both cases because "power" is its own correlative, being equal to the product iv, which is a symmetric function of two correlative quantities and, therefore, unchanged by dualisation.

Again, it may happen that the converse of a theorem is also its correlative. This is the case with the familar T — π transformation, first given by Kennelly in 1899. The equivalence is represented in Fig. 3.

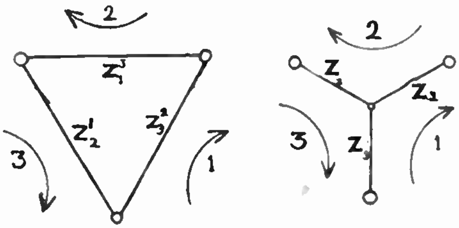

Fig. 3.—Illustrating T — π *Equivalence.*

Let the junctions, meshes, and impedances be numbered as shown, and denote the corresponding admittances by $Y_1 = 1/z_3^2$, $y_2^1 = 1/Z_3$, etc. Then the two networks are exactly equivalent, so far as external effects are concerned, provided that

$$z_2^1 = \frac{Z_1 Z_2}{Z_1 + Z_2 + Z_3}, \qquad \text{..............(1)}$$

with two other relations obtained from this by cyclic

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* This concept is required by the Principle of Duality. It is the analogue of momentum in dynamics.

† It is not seriously proposed that this term be adopted, since there is little use for it. It is introduced merely to balance the table, being correlative to "elastance" which is sometimes used.

interchanges of the numerical suffixes. By dualising this result, we get the formulæ

$$y_2^1 = \frac{Y_1 Y_2}{Y_1 + Y_2 + Y_3}, \text{ etc.} \qquad \ldots\ldots\ldots\ldots(2)$$

While the formulæ (1) enable an equivalent π to be constructed when the impedances of the T are known, formulæ (2) give the inverse transformation. In this case the main use of duality is as an aid to memory.

To obtain the correlative of a network we change meshes for junctions, or junctions for meshes. The correlative is not necessarily equivalent to the original network, but a theorem concerning a network applies to its correlative when dualised.

The well-known reciprocity theorems are correlative to each other, so that one follows from the other. They enable us to generalise the concept of mutual admittance or "transfer admittance" and its associated impedance. The term "mutual conductance" as applied to a valve is strictly a misnomer, since a valve and its associated circuits constitute a unilateral network, that is, a network for which the theorems of reciprocity do not hold. "Transconductance" is a better term.

Correlative Methods of Network Analysis

To determine the response of a network to a given excitation, we apply the fundamental laws embodied in the axioms. This involves writing down a set of linear equations (either in full or in matrix form) and solving these for the particular variables required. The artifice of cyclic currents, or mesh currents, first suggested by Maxwell, is a means of ensuring that Kirchhoff's first law is automatically satisfied. We then write the equations expressing the second law for every independent mesh. For example, let there be n such meshes, and let a current i^m circulate (say, clockwise) in the mth, and let it be opposed by an e.m.f. e^m.* In this mesh, let z_m be the impedance which is not common to any other mesh, and let the impedance common to the mth and kth meshes be z_k^m $(= z_m^k)$. Then, applying Ohm's law to the mth mesh, we have, by Kirchhoff's second law :—

$$z_m i^m + z_1^m (i^m - i^1) + \ldots + z_{m-1}^m (i^m - i^{m-1}) + z_{m+1}^m (i^m - i^{m+1}) + \ldots + z_n^m (i^m - i^n) = -e^m. \qquad \ldots\ldots\ldots\ldots(3)$$

By giving n each value in turn from 1 to n, we get such equations, one for each mesh. If we adopt the convention that the total impedance of the mth mesh is

$$-z_m^m = z_1^m + z_2^m + \ldots + z_{m-1}^m + z_m + z_{m+1}^m + \ldots + z_n^m,$$

so that $-z_m^m$ is the "self-impedance" of the mth mesh, and z_k^m the "mutual impedance" between the mth and kth meshes, we can write the equations in the compact form

$$\sum_{s=1}^{n} z_s^m i^s = e^m \quad (m = 1, 2, 3, \ldots, n) \qquad \ldots\ldots(4)$$

We can also write this set of equations as the matrix equation

$$ZI = E, \qquad \ldots\ldots\ldots\ldots(5)$$

where Z denotes the square matrix $\|z_k^m\|$ and I and E denote the single column matrices $\|i^p\|$ and $\|e^q\|$ respectively. The solution of these equations is

$$I = Z^{-1} E, \qquad \ldots\ldots\ldots\ldots(6)$$

provided Z is non-singular (if Z is singular, the meshes are not independent).

The first theorem of reciprocity is true because the matrix Z (and therefore also Z^{-1}) is symmetric $(z_k^m = z_k^m)$.

The procedure outlined above is probably the most convenient when the sources are of the constant-voltage type, but if they are of the constant-current type, the correlative method can be used. In this, a potential is assigned to each junction in the network, relative to some arbitrary point, preferably one of the junctions. This ensures that Kirchhoff's second law is automatically satisfied. Then, using Ohm's law, a set of equations can be written down, expressing Kirchhoff's first law for each junction. To illustrate the method, consider a network with $(n + 1)$ junctions and call the $(n + 1)$th 0. Assign to this point the potential 0, and to the other n points the potentials $v^1, v^2, v^3, \ldots v^n$. Let the admittance of the branch joining 0 to the mth point be y^m and let the admittance common to the mth and kth points be y_k^m $(= y_m^k)$. Also, let a "flow" f^m leave the network at the mth junction. Then for this junction we have the equation

$$y_m v^m + y_1^m (v^m - v^1) + \ldots + y_{m-1}^m (v^m - v^{m-1}) + y_{m+1}^m (v^m - v^{m+1}) + \ldots + y_n^m (v^m - v^n) = -f^m \qquad \ldots\ldots\ldots\ldots(7)$$

If we now put

$$-y_m^m = y_1^m + y_2^m + \ldots + y_{m-1}^m + y_m + y_{m+1}^m + \ldots + y_n^m,$$

we can write the set of equations for the n junctions in the form

$$\sum_{s=1}^{n} y_s^m v^s = f^m \quad (m = 1, 2, 3, \ldots, n) \qquad \ldots\ldots(8)$$

which is equivalent to the matrix equation

$$YV = F \qquad \ldots\ldots\ldots\ldots(9)$$

of which the solution is, if Y is non-singular,

$$V = Y^{-1} F \qquad \ldots\ldots\ldots\ldots(10)$$

The second theorem of reciprocity is true because the matrix Y is symmetric.

It is unnecessary to write the equation for current balance at the datum point, 0, since this is automatic-

---

* These values are not, of course, instantaneous if the impedances are complex quantities. They represent the amplitudes and phases of waves which all have the same frequency. If several frequencies are present, the analysis is applied separately to each and the results added, in the usual way.

ally included in the *n* equations (7), as we see by adding them. Since $y_k^m = y_m^k$ we get, on summation,

$$\sum_{m=1}^{n} y_m v^m = \sum_{m=1}^{n} - f^m,$$

which expresses Kirchhoff's first law for the datum point. It is not essential that f^m be provided only by a source connected between 0 and the *m*th junction. In general, this junction will have a source in common with every other junction in the network. In this case f^m is the total flow from the *m*th junction, and we have

$$f^m = f_0^m + f_1^m + \dots + f_{m-1}^m + f_{m+1}^m + \dots + f_{n}^m,$$

where $f_k^m = -f_m^k$, so that $\Sigma - f^m = \Sigma f_0^m$. A similar consideration applies to the e^m of equations (4) ; e^m is the *total* e.m.f. acting in the *m*th mesh, and may have parts in common with other meshes.

To complete the duality, we may remark that the result of adding the *n* equations of the type (3) is the equation

$$\Sigma z_m i^m = \Sigma - e^m,$$

which expresses Kirchhoff's second law for the "datum mesh" which carries no circulating current and consists of the impedance z_m.

A network which has *n* independent meshes or *n* independent junctions may be called a "network of the *n*th order." It has in general, $\frac{1}{2}n(n+1)$ branches.

$$v^m = \frac{y_1^m v^1 + y_2^m v^2 + \dots + y_{m-1}^m v^{m-1} + y_{m+1}^m v^{m+1} + \dots + y_n^m v^n}{y_1^m + y_2^m + \dots + y_{m+1}^m + y_{m+1}^m + \dots + y_n^m} \qquad \text{(11)}$$

Suppose that we have such a network, excited by a set of constant-voltage and constant current sources, and that we wish to determine the current in a particular branch. Let this branch be common to the *m*th and *k*th meshes so that its impedance is z_k^m, and let the junctions be numbered so that its admittance is y_k^m. Let the branch contain, in series, an e.m.f. e_k^m, and, in parallel, a flow f_k^m. Then the Principle of Superposition enables us to calculate the current in the required branch due to each set of sources independently, and add the results to get the complete solution. Thus, putting all the *f*'s equal to zero, we calculate i^m and i^k from (6). Then, putting all the *e*'s equal to zero, we get, from (10), the values of v^m and v^k. The required current is then (apart from f_k^m)

$$i = i^m - i^k \pm y_k^m (v^m - v^k)$$

and the fall of potential in the branch is (apart from e_k^m)

$$v = v^m - v^k \pm z_k^m (i^m - i^k) = z_k^m i$$

(the ambiguity of sign would not occur in a practical case).

Alternatively, we can replace each branch with sources by a branch containing only one kind of source, using the equivalence shown in Fig. 2.

It may be noted that if, in equation (7), we put $f^m = 0$ (so that the *m*th junction is passive) and $y_m = 0$ (so that there is no direct connection between the points 0 and *m*) we get Millman's theorem[7] :—

A theorem correlative to this is therefore obtainable by putting $e^m = y^m = 0$ in equation (3). We then get

$$i^m = \frac{z_1^m i^1 + z_2^m i^2 + \dots + z_{m-1}^m i^{m-1} + z_{m+1}^m i^{m+1} + \dots + z_n^m i^n}{z_1^m + z_2^m + \dots + z_{m+1}^m + z_{m+1}^m + \dots + z_n^m} \qquad \text{(12)}$$

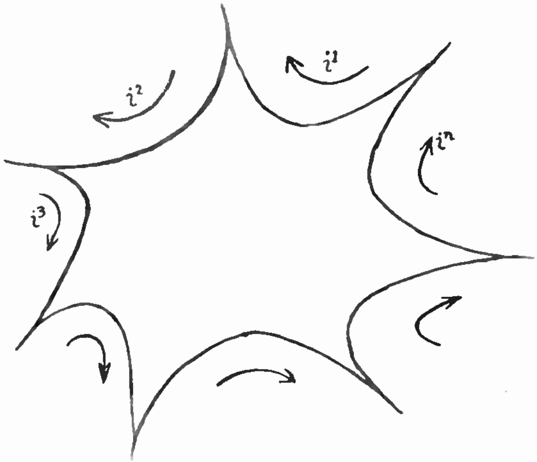


Fig. 4.—Illustrating Correlative of Millman's Theorem.

This gives the circulating current in a passive mesh in terms of the impedances of that mesh and the circulating currents in the meshes with which it shares these impedances (Fig. 4).

The General Star-Mesh Transformation

By a well-known theorem due to Rosen[8], any passive *n*-rayed star in a network can be replaced by an equivalent mesh system, having the same terminals, in which every terminal is connected directly to every other terminal, and the star-point is suppressed (Fig. 5).

The relation between the various admittances necessary to ensure equivalance is given by

$$y_q^p = \frac{y_p y_q}{\sum_{m=1}^{n} y_m}, \qquad \text{(13)}$$

where y_m denotes the admittance between the star-point and the *m*th terminal of the star, and y_q^p denotes the admittance between the *p*th and *q*th terminals of the equivalent network. If there are n branches in the star, there are $\frac{1}{2} n (n - 1)$ in the equivalent network.

Now, by dualising this theorem, we can obtain, in general, a new theorem.

The statement of it runs as follows :—

A passive network consisting of n *meshes, each having an impedance in common with a single mesh, or ring, which contains no other impedance, but not having common impedances between themselves, is completely equivalent to a system of* n *meshes, each of which has an impedance in common with every other mesh, the common ring being suppressed. The relation between the impedances is*

$$z^p_q = \frac{z_p \, z_q}{\sum\limits_{m=1}^{n} z_m}, \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

where the z_m are the impedances of the ring, and z^p_q is the impedance common to the pth and qth meshes in the equivalent network (i.e. $-z^p_q$ is the mutual impedance between the pth and qth meshes).

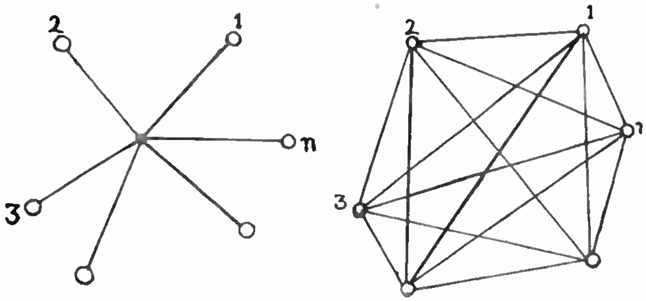


Fig. 5.—Illustrating Rosen's Theorem.

This theorem is difficult to illustrate diagrammatically, except when $n = 3$, when it reduces, like Rosen's theorem, to the $T - \pi$ transformation (Fig. 3). The case $n = 2$ shows the equivalence of two impedances in parallel to a single impedance, just as Rosen's theorem for $n = 2$ shows a similar equivalence for two admittances in series. If there are n impedances in the ring, there are $\frac{1}{2}n \,(n - 1)$ common impedances in the equivalent network.

The restriction that the ring contains "no other impedances" may be removed by imagining such impedances to belong to an additional mesh, which is open-circuited. Similarly, the restriction that there are no common impedances between the meshes of the ring system may be removed by supposing such common impedances to form part of a network external to the ring.

An independent proof of this theorem can be given as follows : Let the meshes be numbered 1, 2, 3,. . ., n, and let the impedances of the ring common to these meshes be $z_1, z_2, z_3, \ldots, z_n$. In the equivalent network let z^p_q be the impedance common to the pth and qth meshes. Let i^m be the circulating current in the mth mesh. Then, in order that the networks shall be entirely equivalent to each other, it is necessary and sufficient that the terminal potentials be the same in each case, for the same values of the i^m. Thus we get n equations of the type

$$\begin{aligned} z_m i^m = {} & z^m_1 \,(i^m - i^1) + z^m_2 \,(i^m - i^2) + \\ & \ldots + z^m_{m-1} (i^m - i^{m-1}) + z^m_{m+1} (i^m - i^{m+1}) \\ & \ldots + z^m_n (i^m - i^n) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (15) \end{aligned}$$

Let us assume that z^p_q can be expressed in terms of $z_1, z_2, z_3 \; \ldots, z_n$ in such a manner that this equation is satisfied identically. It is clear that such an expression for z^p_q must contain z_p and z_q as factors, for if either of these is zero, the corresponding meshes are not coupled to the remainder of the ring system. We also know that the expression must have the dimensions of impedance, that it must be symmetrical in the remaining ring impedances, and that it must reduce to the form (1) when $n = 3$. The last requirement suggests the formula (14). Since this satisfies the other conditions, we substitute it in (15) and get

$$i^m \Sigma z_r = (\Sigma z_r - z_m) \, i^m - (\Sigma z_r \, i^r - z_m \, i^m),$$

that is

$$\Sigma z_r \, i^r = 0,$$

which is satisfied identically, by Kirchhoff's second law applied to the ring. Hence the formula (14) does give the equivalence required.

The theorem just proved is useful in answering questions of the following type : Given a ring system as in Fig. 6, what part of the e.m.f. induced in the mesh q is due directly to a current i^p in mesh p ?

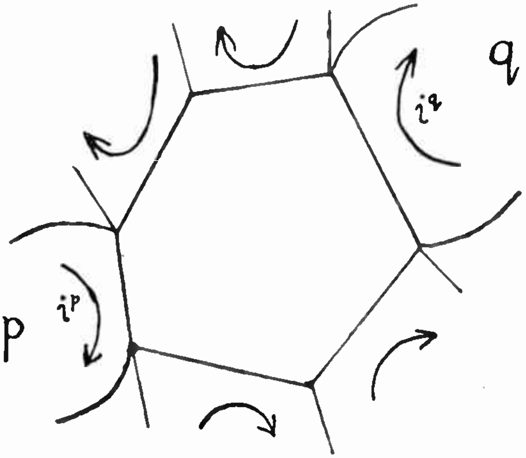


Fig. 6.—Illustrating Application of Ring Equivalence Theorem.

The answer is $i^p \, z^p_q$, where $z^p_q \; (= z^q_p)$ is given by (14).

The theorem can also be used to obtain an equivalent ring circuit for a transformer with multiple windings. In this case, the transformation inverse to (14) is required. This may be written in the form

$$z_b = \sum_{m=1}^{n} z_m^b \quad \ldots\ldots\ldots\ldots\ldots(16)$$

with the understanding that $z_b^b = \dfrac{z_b^a \; z_c^b{}'}{z_c^a}$ where *a* and *c* are points adjacent to *b*. A similar inverse formula applies to Rosen's theorem.

When $n = 3, \frac{1}{2}n\,(n-1) = 3$, and the theorem reduces to the $T - \pi$ transformation. It is then identical with Rosen's theorem.

Quadripoles

A quadripole (four-terminal transmission network, or "transducer") may have any degree of internal complexity, but its external behaviour can be completely described by four complex parameters. In the most usual case, only three independent complex parameters are required, and, if it is symmetrical, only two. Many papers have been published dealing with the analysis and synthesis of such networks, and their properties are now very well known. It does not seem to be generally realised, however, that, in calculations concerning quadripoles much effort can be saved by applying Duality. Consider, for instance, the symmetrical T-network shown in Fig. 7.

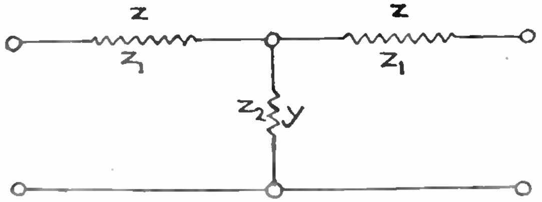


Fig. 7.—Symmetrical T-network.

This has two equal series elements of impedance *z* and a shunt element of admittance *y*. The values of *z* and *y* specify the network completely, but it is usually desirable to express its properties by a different pair of parameters, for instance, the characteristic impedance z_0, and the propagation constant θ. These are given in terms of *z* and *y* by the formulæ

$$\left.\begin{aligned} z_0 &= \sqrt{z^2 + 2\frac{z}{y}}\ ; \\ \theta &= \text{arg cosh}\,(1 + zy). \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots(17)$$

It then follows by Duality that, for the symmetrical π-network (Fig. 8) with series element Z, shunt element Y and characteristic admittance Y_0,

$$\left.\begin{aligned} Y_0 &= \sqrt{Y^2 + 2\frac{Y}{Z}}\ ; \\ \theta &= \text{arg cosh}\,(1 + ZY). \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots(18)$$

Alternatively, we can use impedances to specify all the elements of a T-network and admittances for those of a π-network, thereby obtaining formulæ which are completely correlative to each other. Thus, putting $z = z_1$, $1/y = z_2$, $Y = y_1$, $1/Z = y_2$, equations (17) and (18) become respectively

$$\left.\begin{aligned} z_0 &= \sqrt{z_1{}^2 + 2\,z_1 z_2}\ ; \\ \theta &= \text{arg cosh}\,(1 + {}^{z_1}/_{z_2})\ ; \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots(17a)$$

$$\left.\begin{aligned} y_0 &= \sqrt{y_1{}^2 + 2y_1 y_2}\ ; \\ \theta &= \text{arg cosh}\,(1 + {}^{y_1}/_{y_2})\ ; \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots(18a)$$

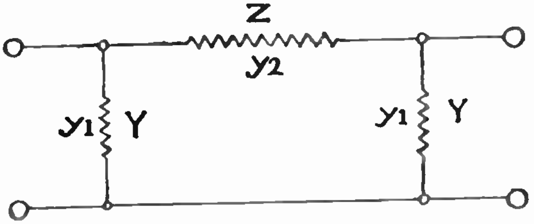
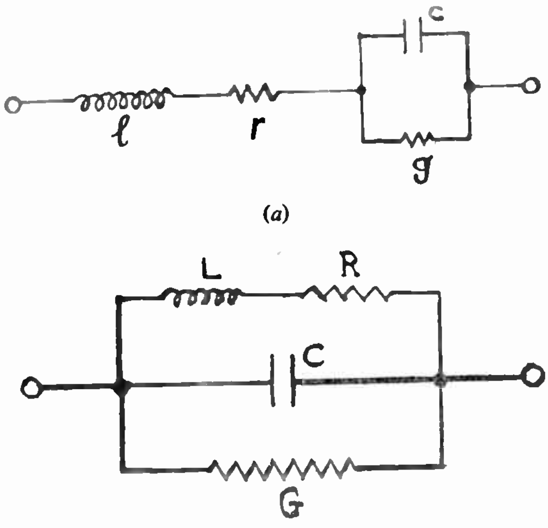


Fig. 8.—Symmetrical π-Network.

It follows that all formulæ for symmetrical π-networks are the same as those for T-networks if admittances are used instead of impedances, the numbering being such that in each case there are two elements with subscript 1 and one with subscript 2.

Resonance.

It is easily seen that the phenomena of resonance and anti-resonance are correlative. Consider the dissipative resonant circuits shown in Figs. 9 (*a*) and (*b*).



(*a*)

(*b*)

Fig. 9.—Correlative Resonant Circuits.

If the currents and potentials are proportional to exp (ut) $(u = 2\pi jf$ in the case of a sine wave of frequency $f)$, the impedance of the system (a) is

$$z = r + ul + \frac{1}{g + uc}, \qquad (19)$$

and the admittance of (b) is

$$\mathrm{Y} = \mathrm{G} + u\mathrm{C} + \frac{1}{\mathrm{R} + u\mathrm{L}} \qquad (20)$$

Now z given by (19) has, *qua* function of u, exactly the same form as Y, given by (20). Hence, as regards variations of u, the impedance in one case behaves exactly as the admittance in the other, assuming that the parameters r, l, g, c, R, L, G, C, are independent of u.

In fact, it usually happens that the loss resistance of a coil, and the leakage conductance of a condenser, vary with frequency. The variation is such that it is often nearer to the truth to assume that they are proportional to frequency than to assume them constant. It may then be convenient to put $r = \omega\rho$, $g = \omega\lambda$, where $\omega = 2\pi f$. The impedance of a coil is then $\omega(\rho + jl) = j\omega(l - j\rho)$, and the admittance of a condenser is $\omega(\lambda + jc) = j\omega(c - j\lambda)$. The ratios ρ/l and λ/c are the loss factors in the two cases, and are often nearly constant over a wide range of frequencies. If we denote the "complex inductance" $(l - j\rho)$ by n, and the "complex capacitance" $(c - j\lambda)$ by k, then (19) and (20) become, respectively

$$z = un + \frac{1}{uk} \qquad (19a)$$

$$\mathrm{Y} = u\mathrm{K} + \frac{1}{u\mathrm{N}} \qquad (20a)$$

It is usually legitimate to use this representation for networks in which dissipation is incidental. When resistance elements are deliberately introduced it may not be valid.

It is possible to extend Foster's Reactance Theorem to reactive networks which contain resistance. It can be shown that the "driving-point" impedance of any network which can be constructed is the same as that of a suitable equivalent network made up of simple structures either of the type (a), Fig. 9, in parallel, or of the type (b), Fig. 9, in series. In general, however, the equivalent network is not physically realisable (negative parameters may occur) so that the extended theorem is of little use in network synthesis.

A Pair of Energy Theorems

To conclude this part of the paper we prove an energy theorem and state its correlative.

If a condenser is charged from a source of static e.m.f. in series with any kind of resistance and inductance (linear or non-linear), then, when equilibrium is established, so that no current flows and the voltage of the condenser is that of the source, the energy lost by the source is twice that stored in the condenser.

Let
V = e.m.f. of source;
C = capacitance of condenser;
v = p.d. across condenser at time t;
i = charging current at time t.

Then $\quad i = \mathrm{C}\dfrac{dv}{dt}$,

i.e. $\quad i\,dt = \mathrm{C}\,dv$

Hence:

$$\text{energy lost by source} = \int \mathrm{V}i\,dt = \int_{c}^{\mathrm{V}} \mathrm{CV}\,dv = \mathrm{CV}^2;$$

$$\text{energy gained by condenser} = \int vi\,dt = \int_{0}^{\mathrm{V}} \mathrm{C}v\,dv = \frac{1}{2}\mathrm{CV}^2$$

This proves the theorem and shows that a quantity of energy $\frac{1}{2}\mathrm{CV}^2$ is dissipated in the charging circuit, whatever its nature may be.

The correlative theorem is :

If an inductor be "charged" from a source of static flow, in parallel with any kind of conductance and capacitance (linear or non-linear), then, when equilibrium is established, so that there is no difference of potential and the current through the inductor is that of the source, the energy lost by the source is twice that stored in the inductor.

These theorems can be extended to cases in which the energy reservoir is created, or enlarged, during the charging process. Consider, for instance, a condenser which is initially uncharged and has its plates far apart. As charge accumulates on them, the plates move towards each other against a mechanical force. Let the instantaneous capacitance be c, reaching a final value C, and let the instantaneous p.d. across the condenser be v, finally becoming V, the e.m.f. of the source. Then:

$$\text{energy lost by source} = \int_{0}^{\mathrm{CV}} \mathrm{V}\,d(cv) = \mathrm{CV}^2;$$

$$\text{energy gained by condenser} = \int_{0}^{\mathrm{CV}} v\,d(cv) = \mathrm{W},\ \text{say}.$$

If the charging current is not oscillatory, $v \leqslant \mathrm{V}$, so the second integral is less than or equal to the first. The case of equality occurs if there are no losses in the charging circuit. Moreover, we have

$$\int_{0}^{\mathrm{CV}} v\,d(cv) = \int_{0}^{\mathrm{CV}} \frac{cv}{c}\,d(cv) = \int_{0}^{\frac{1}{2}\mathrm{C}^2\mathrm{V}^2} \frac{d(\frac{1}{2}c^2v^2)}{c} \geqslant \tfrac{1}{2}\mathrm{CV}^2,$$

since $c \leqslant \mathrm{C}$. Thus

$$\tfrac{1}{2}\mathrm{CV}^2 \leqslant \mathrm{W} \leqslant \mathrm{CV}^2,$$

the left-hand equality occurring when c is constant and equal to C. But if the condenser be now disconnected from the source and discharged through an external circuit while its capacitance is constrained to be constant, it will deliver energy equal to $\frac{1}{2}\mathrm{CV}^2$. Consequently W $- \frac{1}{2}$ CV^2 is the amount of energy absorbed by the mechanical system during the charging process. In the case of an electrostatic voltmeter (or its correlative, a dynamometer ammeter), the losses can usually be neglected, so that one half of the stored energy resides in the deformed (i.e. "charged") mechanical system (usually a spring) and the other half in the space surrounding the condenser plates (or coils).

It is evident that the above discussion could have been made more explicitly general by the use of a word denoting the "capacity" of any receptacle of energy. Expressions for stored energy such as $\frac{1}{2}\,Li^2$, $\frac{1}{2}\,mv^2$, $\frac{1}{2}\,I\omega^2$, $\frac{1}{2}\,SQ^2\ (= \frac{1}{2}\,CV^2)$, $\frac{1}{2}\,Sx^2$, $\frac{1}{2}\,\sigma\theta^2$, show that inductance, mass, moment of inertia (for kinetic energy) and elastance, stiffness (translational or torsional) (for potential energy) could all be included in the meaning of such a word. "Coefficient of energy storage" is somewhat cumbersome. Perhaps *receptance* would be suitable. The dimensions of a quantity to which this name could be applied would depend on the context in which it was used, since, to give energy, it might be multiplied by half the square of a velocity or half the square of a displacement. This difficulty could be overcome by using the terms "kinetic receptance" and "potential receptance" respectively. Of course, the reciprocals of the quantities mentioned above deserve equally to be called coefficients of energy storage, but only in the case of electrical capacitance would such a usage correspond with quantities commonly employed.

Extension to Field Theory

Although the scope of this paper has been deliberately restricted to finite networks in a quasi-stationary state, it may be mentioned that the Principle of Duality can also be found in the bases of the theory of continuous systems and radiation phenomena. The behaviour of a transmission line can be deduced, to a first approximation, by considering it to be composed of a number of discrete meshes having lumped constants, and letting this number tend to infinity in a suitable way. This limiting process does not affect the duality pertaining to the system. However, the theory obtained in this way is not exact, although it is useful for dealing with low-loss lines having lateral dimensions which are small in comparison with the length of the line and with the wavelength of operation.

The exact theory of electromagnetic systems is founded on Maxwell's equations. For a region occupied by matter these are :—

$$\text{curl } \mathbf{H} = \frac{1}{c}\left\{\frac{\partial \mathbf{E}}{\partial t} + 4\pi\frac{\partial \mathbf{P}}{\partial t}\right\} \; ; \quad \ldots\ldots\ldots\ldots(1)$$

$$\text{curl } \mathbf{E} = -\frac{1}{c}\left\{\frac{\partial \mathbf{H}}{\partial t} + 4\pi\frac{\partial \mathbf{M}}{\partial t}\right\} \; ; \quad \ldots\ldots\ldots(2)$$

$$\text{div } (\mathbf{E} + 4\pi\mathbf{P}) = 0 \; ; \quad \ldots\ldots\ldots\ldots(3)$$

$$\text{div } (\mathbf{H} + 4\pi\mathbf{M}) = 0 \; ; \quad \ldots\ldots\ldots\ldots(4)$$

where **E** and **P** denote the electric intensity and polarisation, respectively, in electrostatic units, and **H** and **M** denote respectively the magnetic intensity and polarisation, in electromagnetic units. c denotes the ratio of these units, equal to the velocity of light in free space. The electric polarisation, or electric moment per unit volume, **P**, is due to the displacement of charge, whether bound or free. Both displacement and convection currents are therefore included in the term $\frac{\partial \mathbf{P}}{\partial t}$.

Alternatively, if ρ denotes the volume density of electric charge, and **v** its velocity, we can write (1) in the more usual form

$$\text{curl } \mathbf{H} = \frac{1}{c}\left\{\frac{\partial \mathbf{E}}{\partial t} + 4\pi\rho\mathbf{v}\right\} \; ; \quad \ldots\ldots\ldots(1a)$$

Taking into account the equation of continuity of electricity,

$$\text{div } \rho v + \frac{\partial \rho}{\partial t} = 0 \; ; \quad \ldots\ldots\ldots\ldots\ldots(2a)$$

we can deduce, by taking the divergence of (1a), that

$$\text{div } \mathbf{E} = 4\pi\rho \, , \quad \ldots\ldots\ldots\ldots\ldots(3a)$$

which corresponds to equation (3).

Now equations (1) and (2) can be written in the form

$$\text{curl } \mathbf{H} = \frac{\partial}{\partial jct}\left(j\mathbf{E} + 4\pi j\mathbf{P}\right) \; ; \quad \ldots\ldots\ldots\ldots(5)$$

$$\text{curl } j\mathbf{E} = \frac{\partial}{\partial jct}\left(\mathbf{H} + 4\pi\mathbf{M}\right) \; ; \quad \ldots\ldots\ldots(6)$$

where $j = \sqrt{-1}$. It is clear that (6) can be got from (5), or (5) from (6), by interchanging **H** and j**E**, **M** and j**P**. These two pairs are therefore correlatives, and we have a duality in the fundamental equations. It evidently applies also to the scalar relations (3) and (4), which can be derived from (5) and (6) by taking the divergence and integrating with respect to time, setting the constants of integration equal to zero.

If we add (5) and (6) we get

$$\text{curl } \mathbf{F} = \frac{\partial}{\partial \tau}\ (\mathbf{F} + \mathbf{V}) \, , \quad \ldots\ldots\ldots\ldots(7)$$

where $\mathbf{F} = \mathbf{H} + j\mathbf{E}$, $\mathbf{V} = 4\pi\,(\mathbf{M} + j\mathbf{P})$, and $\tau = jct$. We could, of course, just as well take **F** to be **E** + j**H** and **V** to be **P** + j**M**. Separating the real and imaginary parts of (7), we should then get equations conjugate to (5) and (6). Silberstein,[9] in 1906, considered the complex vector ("Bivektor"), **E** + j**H**, which has some rather interesting properties. In space devoid of matter it completely represents the electromagnetic state. When vector-multiplied by its conjugate it gives Poynting's vector, and when scalar-multiplied it gives the total density of field energy.

Fully to develop the consequences of the duality which is to be found in Maxwell's equations would

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require a paper at least as long as the present one, but a few examples may be mentioned here.

In the first place, it must be emphasised that E and H are *not* correlative. One of them must be multiplied by j in order to get the duality. This implies that, in an electromagnetic field which is varying sinusoidally with time, the correlative space-vectors are in phase quadrature with each other in a non-dissipative medium.

It is clear that correlative types of antennæ are the dipole and the loop. Consider, for instance, a small dipole, and, in the plane which bisects it, a small loop, having its axis along the dipole (Fig. 10).

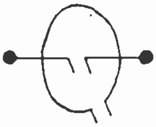

Fig. 10.—Correlative Antennae.

Precisely the same field distribution will be obtained, in free space, from these sources, but the two fields will be polarised at right-angles to each other. As well as setting up correlative fields, these antennæ will present correlative driving-point impedances—the dipole will have a capacitative reactance and the loop will be inductive.

The E- and H-modes of propagation in a wave guide are correlative to each other, as are excitation by a probe and excitation by a loop. It seems probable that a considerable simplification could be achieved by introducing duality into the theory of wave guides at the outset.

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7. J. Millman. " A Useful Network Theorem," *Proc. I.R.E.*, Vol. 28, p. 413, Sept. 1940.
8. A. Rosen. " A New Network Theorem," *Journal I.E.E.*, Vol. 62, p. 916, Nov. 1924.
9. L. Silberstein. " Electromagnetische Grundgleichungen in bivektoriellor Behandlung," *Annalen der Physik*, XXII, p. 579, 1907.

NOTICES

Honours

The Council have tendered congratulations to the following members on their inclusion in the New Year's Honours Lists :—

Wing-Commander N. C. Cordingley, M.B.E., and Mr. J. W. Ridgeway (Members) were appointed Officers of the Most Excellent Order of the British Empire.

Messrs. **C. E. Bottle** and **W. A. Bryce** (Members), **Major P. J. Best** and **F/Lt. W. L. Davies** (Associate Members) were appointed Members of the Most Excellent Order of the British Empire.

Mr. S. L. Robinson (Associate Member) was awarded the British Empire Medal.

The *London Gazette* of December 20th, 1945, gave a Mention in Despatches to **Captain David Peter B. Neave, B.Sc. (Eng.)** (Associate Member), in "recognition of gallant and distinguished services in the field." **F/Lt. W. J. Davies** (see above) has also been mentioned in despatches on two occasions.

Captain Neave was a prisoner of war in Germany from 1941 until 1945.

Obituary

Council regret to record the deaths of:—

Mr. J. W. Gardner (Associate Member), of Darwen, Lancashire, on December 1st, 1945, after a very brief illness. Mr. Gardner was elected an Associate Member of the Institution in 1930.

In Iraq, of **Mr. William Charles Whitfield** (Member), radio communications engineer to the Iraq Petroleum Company. Mr. Whitfield was originally elected an Associate Member of the Institution in 1936.

Correspondence and Changes of Addresses

There are still a number of instances of members failing to advise the Institution promptly of any change of address. It is particularly important that changes should be notified in view of the forthcoming publication of the List of Members.

All grades of members are also asked to be good enough to indicate at least their grade of membership—with their number, if possible—when writing to the Institution. This is particularly essential when forwarding subscriptions.

Future Examinations

The next Graduateship Examination will be held on May 17th and 18th, 1946, and applications to sit must be lodged not later than March 31st, 1946.

Copies of Past Graduateship Examination Papers

The only copies of past examination papers now available are in respect of the May and November, 1942, May, 1943, May and November, 1944, and May and November, 1945, examinations. All other copies are now out of print. The cost of these past examination papers is as follows :—

1 set	2s. 6d.
2 sets	3s. 6d.
3 sets	4s. 6d.
4 sets	5s. 6d.
5 sets	6s. 6d.
6 sets	7s. 6d.
7 sets	8s. 6d.

Radio Trades Examination Board

The next examination of the Radio Trades Examination Board will be held on May 4th, 1946, and will be arranged in various centres according to the number of entries. Here again, applications to sit must be lodged at 9 Bedford Square, London, W.C.1, not later than March 31st, 1946.

Copies of papers set by the Radio Trades Examination Board for 1944 and 1945 only may be obtained at 2s. per set, post free.

In the last Annual Report, reference was made to the discussions taking place between the City and Guilds of London Institute and the Board on the matter of holding a joint examination in Radio Service Work. Final details are now being arranged and it is anticipated that the first joint examination will be held in May 1947. Further details will be published in the Journal in due course.

The Institution of Metallurgists

The Inaugural meeting of the Institution of Metallurgists was held on November 28th, 1945, and the subsequent reception was attended by a number of Presidents of professional Institutions, including Mr. Leslie McMichael.

In view of the notice which appeared on page 3 of Volume 4 (new series) of the Journal, it is interesting to note that the new Institution has been brought into being largely as a result of the co-operation existing between the Iron and Steel Institute and the Institute of Metals, both of whom are Technical Institutions, the former having a Royal Charter. Whilst the Institution of Metallurgists is to be an independent body, its Articles provide for close association with the other two Institutes.

It is intended to interpret "metallurgy" in the wide sense appropriate to the diverse methods now employed in studying metals and alloys and in making use of them, and to encourage scientists whose main interests lie in metallurgy to become and to designate themselves metallurgists.

The first President is Dr. Harold Moore, formerly Director of the British Non-Ferrous Metals Research Association, and the Secretary is Mr. K. Headlam-Morley, from whom further particulars may be obtained at 4 Grosvenor Gardens, London, S.W.1.

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TRANSFERS AND ELECTIONS TO MEMBERSHIP

The following elections and transfers were recommended by the Membership Committee at their meetings held on November 27th and December 18th, 1945, and January 23rd, 1946. At these three meetings, the Committee considered a total of 137 proposals for transfer or election to Graduateship or higher grade membership

Transferred from Associate Member to Full Member

HOLMES, Robert Gerlan Dale	Slough
LENNIE, George, B.Sc.	Pinner

Transferred from Associate to Associate Member

ASKEW, Raymond, B.Sc.	Darlington
COURT, Frederick Charles	London, S.W.
ERDOS, Paul	Edinburgh, 3
HAY, George Angus, M.Sc.	Leeds
KERRIDGE, Leslie Alec	Christchurch
MASON, Stanley Philip	Sutton Coldfield
McCARTNEY, Angus	Hitchin
MILLS, Ronald James	Isleworth

Transferred from Graduate to Associate

SUTCLIFFE, John Anthony	Morecambe

Transferred from Student to Associate

ANNS, John Joseph, Major	London, S.W.4
DALE, Thomas George Martin	Twickenham
GRIFFITH, John Edward Llewelyn	Maidenhead
HAYNES, Bernard Frank	Kingston-on-Thames
HISCOCK, David	Slough
JOSEPH, Norman	Cardiff
MANN, Francis Charles	Leigh-on-Sea
ORRIN, John Noel	Liverpool, 17
SHERLEY-PRICE, Desmond Reginald	London, W.2
TOMS, David Morgan Storer	Sidcup

Transferred from Student to Graduate

FOLAN, Aidan John Patrick	Dublin, N.W.5
O'REILLY, William Gerard	Dublin

Elected to Associate Member

AIKMAN-SMITH, Gavin James	Edinburgh
BEAL, William Kenneth, Major, B.Sc. (Hons.)	Richmond
DAVIS-RICE, Alfred	Welling
HANDOVER, Paul, Lt.-Cmdr.	Banstead
HEATLEY, Reginald Playfair	Petts Wood
JAGGARD, Thomas Norman, Lt.-Cmdr.	Maldon
KEALL, Arthur Lockwood, Lieut., B.Sc.	Wellington, N.Z.
LAMB, Ian Claud Imlach	Blackpool
LAWRENCE, Peter Stafford Hayden, B.A. (Hons.)	Windsor
McDERMOTT, Denis	Edinburgh
MESSENGER, Charles Henry, Lieut.	London, E.17
MIDDLETON, Ronald George, Lt.-Cmdr.	Croydon
MILLER, John Robert	Colwyn Bay
MORTLOCK, Alfred, B.Sc.	New Barnet
ROBERTSON, Peter William Victor	Dartford
SKERREY, Cyril Ernest	London, S.W.7
SOUNESS, John, Major	Scotland
SPEARS, Ralph Aubrey	Liverpool
TOMLINSON, Frank	Hendon, N.W.4
WEBBER, Cyril William Arthur	Montgomery
YOUNG, Henry William	Ashford

Elected to Companion

HUGHES, George Young	Eyemouth

Elected to Associate

ALLEN, Leon Connel	London, W.C.2
APLIN, Frederick Edwin	Worcester Park
APPLIN, Ivor George	Somerset
BAILEY, Arthur Joseph	Manchester, 9
BAYLISS, Athol Thomas	Oxford
BEATTIE, Alfred George Noel	Northampton
BENNETT, Richard Edward	Bexleyheath
BEVERIDGE, Stuart	Redditch
BIGMORE, James	London, S.W.20
BONNETT, Reginald Owen, Lieut.	Tunbridge Wells
BOYCOTT, Douglass Harvey, Lieut.	London, S.W.1

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Elected to Associate (contd.)

BRADLEY, Howard Allan, B.A. (Hons.)	Sheffield, 10
BROOK, Leslie Norman	Bristol
BROOKS, James Stuart	Southsea
COPLEY, Darrell Gordon, Fl./Lt.	Edinburgh
COPLEY-MAY, Victor Julian	London, S.W.14
COTTY, William Feltham	S. Africa
CRABTREE, William Herbert	Nuneaton
DOHERTY, Edmund Joseph	London, S.E.22
DOOLE, Wilfred John	Wellington, N.Z.
DUNMORE, Harold Walter	Leicester
ECKBO, John Spargo, B.Sc. (Eng.), Lieut.	Johannesburg
ELLIS, John Henry	Walton-on-Thames
ETTINGER, Georg Michael, B.Sc. (Eng.)	London, N.W.6
EVANS, John Dennis, B.A. (Hons.)	Ruislip
FLACK, Maurice	Northampton
FRYER, Frank Hardman	Watford
GILLETT, Ronald Ernest	London, S.E.10
GRANT, John Reginald, Captain	Belfast
GRENFELL, George Francis	Woodford Green
HARRISON, Harold Mellor, B.Sc. (Eng.), Hons.	Oldham
HEATH, Bernard Gerald	Southport
HENDRY, John	Glasgow, S.1
JORDAN, Wilfred Irving, B.A.	Bristol
KANTAWALA, Mahmood Kaderali	Tanganyika
LEECE, John, Lieut.	Cork-in-Cartmel, Lancs.
LUNT, Joseph Albert, B.Sc.	Ulverston
MINNS, Harry Albert	London, S.E.24
MOAT, William Wilson	Mablethorpe
MORGAN, Alan Paul	Chalfont-St.-Giles
MORRIS, Roy, B.A. (Hons.)	Shifnal, Salop.
NIXON, Herbert, Lieut.	Wirral
PAUL, Edward Frank	Eastbourne
PEDDLE, Hubert Leslie	Alton, Hants.
PETERI, William Herman	London, S.W.1
SAHOTA, Ranjit Singh	Dares Salaam
SMITH, Eric Charles	London, E.11
SMITH, Gordon Shirley	Stanmore
SMITH, Leslie Frederick, Fl./Lt.	Surbiton
SPRUCE, Thomas Albert	Manchester
STINTON, Leslie Giles	Walsall
THOMAS, Francis John	Shrewsbury
TONGUE, Arthur Eric	Coventry
TURNER, George Christie, B.Sc.	Doncaster
TYE, Ronald William	Teddington
VEIL, Joseph Denis Leonce	London, S.W.15
WEBSTER, James Hedley	Royston

Elected to Graduate

MURPHY, Michael Patrick	Co. Wexford

STUDENTSHIP REGISTRATIONS

The following Registrations were completed in the period ending October 19th, 1945, but were not included in the December issue of the Journal.

SHAW, Henry	Co. Down
SHEPHERD, Norman Hemsworth	Dunedin, N.Z.
SIMMONDS, Reginald Ernest	Hornchurch
SMALL, Alfred William	London, S.E.27
SMITH, George Donald	Wisbech, Cambs.
SMITH, Herbert Alfred	West Drayton
SMITHSON, Warren Talbot	Slough, Bucks.
STALKER, Dudley Clarence	Victoria, Aust.
STAUNTON, Eric Douglas	Orpington, Kent
STERNKUKER, Juda	Southend-on-Sea
SUGDEN, Stuart Morton	Formby, Liverpool
SZYMANSKI, Roman	Devonport
TAAFFE, Peter Albert	Muswell Hill, N.10
TAME, Ronald James	Dorchester-on-Thames
TARRANT, James	Victoria, Aust.
THOMAS, Cyril Robert	Rhondda, Glam.
THOMPSON, Arthur Lawrence	Melbourne, Aust.
THORNTON, Peter Beresford	Doncaster
TOUCH, Clifford William	Thrapston, Northants.
TROTTER, John Raymond	Jarrow, Co. Durham
USHER, John	West Hartlepool
WALDEN, Oliver Charles	Pocklington
WALSH, Kevin Daniel	Bradford
WARD, Douglas Arthur	Palmers Green,
WELHAM, Frederick George	Worksop
WILLIAMS, Clifford Henry	Hereford

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STUDENTSHIP REGISTRATIONS (*contd.*)

The following were Registered as Student members of the Institution at meetings of the Membership Committee held on November 27th and December 18th, 1945, and January 23rd, 1946. At these meetings, the Membership Committee received a total of 58 proposals and there were also some amendments of proposals lodged for election to higher grades, but accepted for Studentship Registrations. A total of 59 Registrations have been approved by the General Council.

ABOBA, Joseph Julian	Alexandria
ALTEKAR, Yashawant, B.Sc.	Poona, 5
APTE, Anand, B.Sc.	Poona, 5
ARBUTHNOT, Francis George	West Australia
ARNOLD, Frederick Peter	East Croydon
ARORA, Ahendra Nath	Calcutta
BAKER, Ransome Charles Lawrence	Mitcham
BROOKE, Thomas Reginald	Sleaford
BUGGS, Leslie William	London, S.E.15
CAHILL, John Henry William	Colchester
CANNON, Charles William Douglas	Clacton-on-Sea
CARCASSON, George Vincent	London, S.W.3
CLEGG, Robert James	Auckland, N.Z.
COCKS, Edward George	Eastbourne
COOK, Adam	Glasgow
DAY, William David	Swindon
DODDS, John Arthur	South Harrow
ELLIS, Harry	Barnoldswick
ELLIS, Stanley Victor Keith	New South Wales
EPSTEIN, Jan Leo	Palestine
EVANS, Harold Hoadley	Brisbane, Australia
FACER, Jack	Ramsgate
FELLOWS, Horace	Wolverhampton
FIELD, Harold Edward	Queensland, Australia
FOSTER, Anthony Charles	London, S.E.19
GASKING, Alan James Franics	Tottenham, N.15
GIBBS, John Bernard	Mansfield
HACKING, Joseph Randal	Blackpool
HALLIDAY, Robert Ernest James	Weymouth
HARRIS, John	London, W.9
HEMERY, Norman Valentine	Ilminster
KING, Kenneth William Alec	Malden
KNOWLES, William	Mansfield

MANGRU, Soney James	London, E.C.1
MARNITZ, Joseph William	Natal
McNAMARA, Staunton	South Australia
MITRA, Sukhendra Nath, M.Sc. (Hons.)	Croydon
MORLEY, George William	Wallington
MORLEY, Gilbert	Manchester
NESS, Walter	Glasgow, S.W.2
NIJHAWAN, Suraj Kumar, B.Sc.	Lyallpur
PLANT, Arthur Frederick	King's Lynn
RAJKUMAR, Gnanapragasam Manuelpillai	Ceylon
ROCHESTER, Frederick Colin	Chester-le-Street
SALES, Victor Robert	Nottingham
SAMPSON, Shadrock	Bangalore, India
SARIN, Jagdish Chandra, B.Sc.	Sialkot, India
SHARMA, Dharm Sheel, B.Sc.	Bombay
SIMMONS, Henry Robert William	Southall
SILVERWOOD, Stanley George	NewSouth Wales
SINHA, Kailashnath, B.Sc.	Meerut, India
SULLIVAN, Richard Kevin	Sydney, N.S. Wales
SWAN, Raymond	North Shields
TURNER, Douglas	Mountsorrel, Leics.
VARTY, Kenneth Armstrong	Wallsend-on-Tyne
WATSON, Charles Mitton	Colwyn Bay
WILLIAMS, Frank Sydney Robert	Sydenham, S.E. 26
WILLIAMS, John Douglas	Christchurch
WOMERSLEY, Aubrey	Bradford

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GRADUATESHIP EXAMINATION

PASS LIST—NOVEMBER 1945 (First List only)

122 candidates entered for the November, 1945, examination, compared with 139 candidates who wrote the May, 1945, examination, making a total of 261 for the year, compared with 202 for 1944.

A subsequent Pass List will be published after further scripts from overseas centres have been examined. Prize-winners in respect of the two examinations held during 1945 will be announced in May. (S) indicates Registered Students of the Institution.

Passed entire Examination

The following list includes candidates who are exempt from, or who have previously passed, part of the examination and who have now passed the remaining subjects.

BETTS, Charles Anthony Blundell (S)	Leigh, Lancs.
CLARK, Robert (S)	Liverpool
DAVIS, Haskel Barshoch (S)	Tel-Aviv
FARLEY, William Morrison (S)	London, S.W.11
FEHER, George (S)	Haifa
FERGUSON, Fergus Esler (S)	Belfast
HAMILTON, James Richard (S)	Greenford
HUNT, George Ernest (S)	Alton, Hants.
HUTSON, Geoffrey Henry (S)	Canterbury
KING, Christopher John (S)	Bromley, Kent
MANN, Francis Charles (S)	Leigh-on-Sea
MURPHY, Michael Patrick	Dublin
NAVIN, Edmund (S)	Newry, N. Ireland
SAGE, Ronald William (S)	Sittingbourne
SAUNDERS, Eric George Thorp (S)	Walsall
SMITH, Granville (S)	Henlow
STEIN, Gabriel (S)	Jerusalem
STIBBE, Harry (S)	London, S.E.20
TOLL, John Walker (S)	Hitchin
TURNER, Lewis Edgar	Deal
WARD, Geoffrey Martin (S)	Lincoln
WEINBERG, Hans (S)	Tel-Aviv
WIESNER, Adolf Leopold (S)	London, W.9

The following Candidates passed Parts 1, 2 and 3 only

CRITCHLOW, Philip Sydney	Tipton, Staffs.
PATERSON, John Lindsay (S)	Scopwick, Lincs.
TATE, Frederick Charles (S)	London, N.4
WALLWORK, Allan (S)	Accrington
WULKAN, Alfred (S)	Haifa

The following Candidates passed Parts 1 and 2 only

BEAUCHAMP, Kenneth George (S)	Coventry
CHRISTIAN, Robert Gregory (S)	Billericay
COOPER, Wallace George (S)	London, N.4
KRAIGER, Alec (S)	London, N.W.3
SCHLESINGER, Werner Ludwig (S)	Port Elizabeth
SHACKLE, George Edward (S)	Bolton
SUGDEN, Stuart Morton (S)	Liverpool
SYKES, Arthur Ferguson (S)	Wakefield

The following Candidates passed Parts 1 and 3 only

BASSETT, William George (S)	Dublin
MULGAN, David Kennaway	London, N.13

The following Candidates passed Parts 2 and 3 only

MICHIE, Joseph Lawrence (S)	Skelmerdale
STULAND, Tor (S)	London, W.2

The following Candidate passed Parts 3 and 4 only

GALPIN, Harold Henry Albert (S)	Welling, Kent

The following Candidates passed Part 1 only

BROADBERRY, Noel Edward (S)	Dublin
CADOGAN, Alexander Joseph (S)	London, S.W.11
CROSS, Edward Charles	Hailsham
EATON, Ernest Steckle	Novia Scotia
INSTONE, Allan Arthur (S)	Cheltenham
MILLETT, David Trevor (S)	Rhyl
MURTAGH, Patrick Joseph (S)	Co. Cavan
O'HIGGINS, Colm (S)	Dublin
PELOW, James George (S)	Dublin
PROCTOR, Antony Charles (S)	London, N.W.9
STAUNTON, Eric Douglas (S)	Orpington, Kent
SWAN, Raymond (S)	North Shields
TAAFFE, Peter Albert (S)	London, N.10
TOWNSEND, Charles Alfred (S)	London, S.W.19
WILLIAMS, Kieran Francis (S)	Dublin

The following Candidates passed Part 2 only

LEWKOWITZ, Walter Richard (S)	Haifa
STERNKUKER, Juda (S)	London, W.2

The following Candidates passed Part 3 only

BROMBERGER, Berthold (S)	Jerusalem
PRIOR, Reginald Howard William (S)	Canterbury
WEISS, Zoltan Edward (S)	Montreal

The following Candidates passed Part 4 only

MASEYK, Norman Leslie (S)	Allahabad
McGOVERN, Michael (S)	Dublin

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STEATITE FOR HIGH FREQUENCY INSULATION

By James M. Gleason, B.Sc.*

(A Paper read before the Institution of Radio Engineers (Australia), Sydney Division, on January 18th, 1945)†

The developments in radio and radio frequency applications have necessitated the improvements of dielectric materials. Good insulation is a factor of utmost importance to attain the optimum performance of radio equipment. High-frequency electrical apparatus, it was found, needed far better insulating material than had been used before. To meet this demand for improved insulation a material better than electrical porcelain was developed.

Over the period of electronic development, many ceramic insulating materials were investigated, but their application was determined by their dielectric behaviour on one hand and their difficulty of manufacture on the other. It may be of interest to mention a few of them here. In manufacture the ceramics may be divided into two main divisions: Those formed into the desired shapes before firing to vitrification, and those whose fabrication is accomplished after the material is vitrified. In the prefabricated form are porcelain, steatite alumina, and magnesia ceramics. Allowance must be made for considerable shrinkage (as much as one-third the total volume of the piece, corresponding roughly to one-eighth in linear dimension) which occurs during the firing process. Experience has enabled the manufacturer to estimate the shrinkage to a very fine degree, and it is often possible to manufacture ceramic insulators to within one-thousandth of an inch in several inches of length. Pieces fabricated before firing may also be ground to exact size after firing, provided the ground surface is flat or of simple configuration. Tapped holes and similar items cannot be ground after firing economically, and must be "shrunk-to-size" by proper design and accurate control in heat treatment.

Material of the type which is fabricated after undergoing a vitrifying heat treatment can be illustrated by the glass-bound mica materials. These materials are worked in the same manner as metal, and can be ground, drilled and tapped to exact size, but the wear on the tools is prohibitive. In this class is fused quartz. From a purely electrical point of view quartz has long been known as the best for insulation. However, it is very costly and the sources of supply are few and far between. For precision radio instruments, where cost is of no importance, quartz is occasionally used.

Some 25 or 30 years ago its was found that the inclusion of a percentage of talc (magnesium-silicate in natural forms) in porcelains greatly improved their hardness and strength. Increasing percentages of this material were used until by 1926 methods had been developed for using this material also as the body of the porcelain. The "mineral" magnesium-silicate exists in nature as soapstone, or "steatite," the name given to massive talc.

From the vast research programme for a suitable high-frequency insulating material the one composed mainly of talc, treated with the proper plasticising agents and phrochemical fluxes, lent itself to fabrication by any of the various methods of moulding and heat treatment known to the ceramic manufacturer to the desired shape and size of the electrical engineer. Not only did this relatively new material have exceptional mechanical properties but it answered practically all the electrical requirements.

The growing importance of the ultra-high-frequency spectrum, together with the general trend towards the attainment of higher efficiency in all classes of electronic equipment, has concentrated attention on the importance of the steatite type dielectric. Therefore, the scope of this paper is the explanation of various properties of low-loss steatite, and by the support of facts collected over a period of years to demonstrate its superiority over other types of insulating materials for use in the high-frequency field of electrical engineering, electronics.

For practical purposes, materials used in electrical engineering are divided into conductors and insulators. A conducting material allows a continuous current to pass through it under the action of a continuous e.m.f. An ideal insulator (more correctly called a dielectric) allows only a brief transient current which charges it electrostatically. This charge or displacement of electricity produces a counter e.m.f. equal and opposite to the applied e.m.f., and the flow of current ceases. A substance may practically stop the flow of current when the applied voltage is sufficiently low, and at the same time be unsuitable as an insulator at high voltages. Some materials, which are practically non-conducting at ordinary temperatures become good conductors when sufficiently heated.

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* Chief Ceramic Engineer, General Ceramics and Steatite Corporation, Keasbey, New Jersey, U.S.A., and recently in Australia with Ducon Condenser Pty., Ltd.

† Reprinted in accordance with the reciprocal arrangements made between the I.R.E. (Australia) and the Brit. I.R.E.

A voltage causes several phenomena in ceramic insulation. The first phenomenon consists of electron flow from one side of the atom to the other as the polarity of the impressed voltage changes. Thus, in a perfect dielectric the current is 90 degrees ahead of the voltage. Secondly, " dipole polarisations " enter into the picture, that is, positive and negative charges located away from the centre of a molecule tend to rotate as the polarity of the impressed current changes. Ceramic insulators may be considered as permanent dipoles. As the viscosity of the dielectric material increases the slower the dipole polarisation cycle occurs, thus coupled with the fact that ceramics are of a heterogeneous structure, which also tends to slow up the lining up of the dipoles, and hence the dielectric constant, or relative permittivity of the dielectric is lowered. The rotation of dipoles causes friction within the dielectric and this friction develops heat; therefore it is necessary for the dipole action to be limited or held in one position to attain the least permitted and still form no excessive heat that may affect the viscosity and increase the rate of polarisation. This holding of the dipole in one position, that of either at 90 degrees to the direction of flow of the current, or at least not allow a complete lining up of the dipoles, could be accomplished theoretically by the high-frequency used in electronic engineering, that is, the frequency is higher than the relaxation frequency of the dipole. With the possible range of frequencies in the electronic field, it is not often practicable to use a frequency which will accomplish such an ideal set-up, therefore some leakage of current occurs.

When the alternating voltage is applied to a capacitor the resulting current will have a small component in phase with the voltage. The phase angle ϕ between current and voltage will differ from 90 degrees by the small amount δ, known as the loss angle. The power factor of the dielectric is expressed as $\cos \phi = \sin \delta$. For all vitrified ceramic materials, and, in fact, for all sound insulating materials, the angle is so small that $\sin \delta = \tan \delta = \delta$ (when δ is expressed in radians).

The power factor is the fraction of the energy lost during a cyclic charging and discharging of a condenser formed by the dielectric. The amount of energy stored in the dielectric at a given field is proportional to the dielectric constant. The product of the power factor and the dielectric constant is therefore a measure of the actual loss in the dielectric, and it is known as the " loss factor." All dielectrics show energy losses in alternating fields.

This loss of energy transforms itself into heat, due to the resistance of the insulating material. The loss of energy, therefore, has a direct bearing on the behaviour of the dielectric in use.

Since it has been illustrated how the polarisation is developed in a dielectric, we may now turn our attention to outside influences which effect its dielectric behaviour. The term " dielectric behaviour " usually refers to the variation of dielectric constant, power factor and loss factor, electric breakdown strength, volume and surface resistivity with frequency, temperature, voltage and composition.

Chemical Composition and Structure

The term " ceramics " is derived from the Greek word " keramos," and its translation in a crude sense is " fired stuff," that is, any inorganic material or combination of materials whose structural qualities and properties are dependent on a heat treatment or burning (firing) operation.

The principal raw inorganic materials are clay, feldspar and flint, all ground to a very fine grain size.

In compounding a body the raw materials are mixed either in excess water for proper mixing, if any of the clays are in lump form, or, when all finely ground raw materials are available they can be thoroughly mixed dry, then wetted to attain the desired plasticity. This water, added for mechanical purposes, is dried out slowly after the desired forming operation is completed. The main methods of forming ceramics are casting, throwing, jiggering, extruding, wet pressing, and dry pressing. In the order mentioned the water necessary for forming decreases from the first mentioned which would need approximately 40 per cent. water down to the last method, which requires no water at all. However, complete dry mixing has not been a success, so that, in order to get a uniformity of mixing, at least 15 per cent. water should be added, and in the case of dry pressing the wet material is granulated to coarse particles of a known grain size distribution, the water is then dried out completely and bonding of the particles is accomplished by the use of binders subjection to a high uniform pressure in hardened steel dies.

In the unfired body the clay substance acts as the plastic constituent and imparts to the body its workability. The methods of shaping ceramic materials are based on the plastic quality of the clay. Feldspar and quartz have the effect in an unfired body of decreasing the plasticity of the clay and of decreasing the rate of shrinkage during the drying process. They may be termed " opening " materials. Their chemical effect takes place at high temperatures during the firing operation.

As the shaped article is subjected to a rising temperature the chemically combined water is removed until at approximately 1100° F. the removal is complete, giving the following reaction from the clay :

$$Al_2O_3 + 2SiO_2 + 2H_2O \longrightarrow 2H_2O\uparrow + Al_2O_3 + 2SiO_2$$

At a slightly higher temperature, approximately 1500° F., the alumina and silica recombine in a different

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ratio to form crystals of mullite and free silica, a reaction shown by the following equation :

$$3Al_2O_3+2SiO_2 \longrightarrow 3Al_2O_3+2SiO_2$$

At 2200° F. the mullite crystals begin to grow and the excess free silica is present as cristobalite and tridymite. The development of mullite crystals would bind the body together to some extent by crystal intergrowth without the formation of any liquid bond. Not until the temperature of 2820° F. is reached is it possible to produce any liquid from clay alone that would tend to produce vitrification. If any impurities are present in the clay the glass would begin to form earlier, but it still would be at a most uneconomical temperature to fire a body made of such an inexpensive base.

A fluxing agent is needed, and that is where feldspar comes into the picture. In the presence of silica, the feldspar begins to melt at approximately 1800° F.

Since in a clay body SiO_2 is always present in a finely divided and active condition resulting from the decomposition of the clay, this liquid is quite readily formed. Impurities, such as CaO in the feldspar and clay, lower this eutectic temperature around 200° F. However, the viscosity of this liquid permits only a negligible amount of reaction with the rest of the body.

To obtain proper viscosity to permit more reaction other auxiliary fluxes may be added such as $CaCO_3$ and these reduce the viscosity quickly, so quickly, in fact, that it is necessary to control the firing so as not to get a deformed article. The flint or silica completes its purpose over this period, by acting as a skeleton, holding the glasses in shape. If the body mixture is raised higher than is necessary, more and more of the silica is taken into solution, and finally the skeleton is so weakened as to be no longer able to hold the original form of the body, and it deforms. Therefore, it can be said that what the ceramic engineer attempts to do is to compound a mixture of clay, feldspar, flint, and auxiliary fluxes when needed, to give the necessary plasticity and prefired mechanical strength to the body and then in the pyrochemical reactions ensure that he obtains just the correct amount of glass formed necessary to take most of the clay into solution and still not enough to weaken the structure through too great a glass formation and have just enough silica so as to make it possible to densify the body at an economically low temperature without distortion from too little silica. By covering the reactions which occur in the firing of a porcelain mix it will be easier to visualise the reaction occurring in a steatite mix.

The resulting fired porcelain body contains approximately 50 per cent. of feldspatic glass with interlocking mullite crystals, undissolved clay and silica. Feldspar is used in porcelain bodies because it has a long firing range and it is comparatively inexpensive. However, it is the one large item that prevents porcelains from ever becoming good dielectics at high frequencies. The glass formed contains alkali ions, and therefore they have a rapid rate of change in electrical properties with temperature variation. They also have large power losses at high frequencies. When the feldspar content is kept low and the glass matrix is formed by the aid of alkaline earth compounds such as $BaCO_3$, $CaCO_3$, $SiCO_3$, the power factor decreases and the dielectric strength rises. However, there is a limiting factor, feldspar combines with the clay to a greater extent and forms a more homogeneous structure than do any of the alkaline earths. Flint and feldspar, and even clay have far too great an abrasive action to allow a mixture to be pressed in the dry state in a steel die for an economical length of time without wearing the die beyond the allowable limits of dimensional accuracy permissible for electrical requirements.

Talc, a magnesium silicate, having a hardness of one on Moh's scale, was found to act as a flux and could be substituted for the feldspar. Further experiments passed through a field of composition consisting of 40 to 60 per cent. talc. Crystal structure was studied and the chief crystalline compound was found to be of cordierite with a molecular formula of

$$2MgO \;.\; 2Al_2O_3 \;.\; 3SiO_2$$

The cordierite body is also on a eutectic point and has such a short vitrification range that it is impracticable from a manufacturing standpoint, at least where the body has to be fired to vitrification. This body has electrical characteristics just a little better than electrical porcelain. It has very good heat shock properties, however, but from the manufacturing angle the abrasiveness and firing behaviour still limit its use.

Experimental work along the line of producing a synthetic body composition approaching natural lava was carried out. Talc was the only mineral that could impart enough MgO with silica to the extent of forming a crystal structure predominantly of clinoenstatite and cristobalite and still keep the abrasive action extremely low.

Talc alone, when fired, gives off its water of crystallisation between 1470 and 1540° F. and the talc molecule changes to enstatite and amphorous silica according to the formula

$$\underset{\text{(Talc)}}{3MgO.4SiO_2.IH_2O} \rightarrow H_2O + \underset{\text{(Enstatite)}}{3\,(MgO\;.\;SiO_2)} + \underset{\text{(Amorphous Silica)}}{SiO_2}$$

Most of the commercial talc of high purity will analyse closely to $4MgO \;.\; 5SiO_2 \;.\; 1\tfrac{1}{2}H_2O$.

Instead of the normal silica inversion from tridymite to cristobalite as the talc decomposes, the silica comes out as cristobalite and is in a more chemically active state than the tridymite would be.

The eutectic between talc and clay is 70 per cent. talc and 30 per cent. clay.

Incorporation of alkaline earth fluxes helps to lower the eutectic and also increase the amount of liquid formed.

A eutectic composition is a very difficult mixture to fire since it has an extremely short firing range. To increase the firing range the MgO and Al_2O_3 must be increased. When the limit of this variation is reached, a decrease of the Al_2O_3 with other constituents held constant will again give an increase in firing range.

Of the crystals developed upon firing a mixture of pure talc and clay there may be the following pairs of crystals touching each other :

(1) Cristobalite and clinoenstatite.

(2) Cristobalite and mullite, and

(3) Mullite and clinoenstatite.

There will be 50 per cent. of each component at the interface of any pair. In pair number (3) there will be reactions in the solid state forming a very thin film of cordierite.

When a third component is added, as in the case of the alkaline earth flux, three more types of contact interfaces exist. Each of these has its eutectic temperature. In this manner it is possible to gain a longer firing range and be able to keep this body from deforming.

Throughout the experimental work microscopic checks on the body compositions favoured the theory of more and more interlocking clinoenstatite crystals and less and less glass in the fired body. To accomplish this a sharp, longer cooling period near the maximum firing temperature will practically eliminate mullite and glass.

It appears that all of the excellent electrical properties of the Steatite dielectric can be attributed to the formation of prominent clinoenstatite crystals, and their interlocking structure gives the high mechanical strength peculiar to this type of ceramic material.

Just enough clay is kept in the body composition to ensure good working properties before firing, and the trend is toward lowering the clay content still further and depending on organic binders to hold the grains together in all the methods by which this material can be formed. Steatite can be formed by casting, extrusion, wet and dry pressing methods.

To accomplish very close control over the finished product, exceptionally close control over the raw materials must be exercised. The raw material supplier must guarantee chemical uniformity and a degree of grinding that shall not vary from bag to bag and preferably from shipment to shipment. The specification for the raw material supplier is arrived at by a never slackening control by the manufacturer to gain the knowledge of what effect the various changes in each of the raw materials used in the body composition may have in the finished product. Impurities resulting from careless selection of the ore, grinding in unclean mills, shipping in bags easily penetrated by dirt and moisture, cannot be tolerated by the steatite manufacturer.

With a continuous check on the amount of mixing water, the percentage of solid content in the binders added, and overall accurate weighing of raw materials and their mixing time, it is possible to produce steatite with a tolerance of ± ·005 in. but only by grinding after firing or by a special batch and article selection can very low tolerances such as ± ·001 in. be held.

Since talc is the main constituent of the steatite body it is important to list here the prerequisites of a suitable talc.

Flaky talc is not the best for extrusion because it does not develop plasticity upon fine grinding. However, it can be used in dry pressing methods. The best usable talc is distinguished from talc schist principally by its very fine grained particles.

To prevent high dielectric losses at high voltages and frequencies, the talc must be below 1·0 per cent. in iron content. In lower grades of insulators, where colour does not matter, the iron oxide may be as high as 1·5 per cent.

The power factor is lowered slightly, and the mechanical strength of the insulator is increased by the presence of CaO; however, the firing range is seriously shortened. The limit of CaO in talcs for steatite body use is not more than 1·5 per cent.

An excess of glass, which greatly increases the power loss, is formed more readily when the Al_2O_3 content is higher than 1·5 per cent. in the raw talc. For use in cordierite bodies the presence of high Al_2O_3 in the talc is preferable since it lessens the amount of abrasive alumina to be added to the body.

The ratio of MgO to SiO_2 should be within the limits approximately (29·5 to 32·5) per cent. MgO : (58·5 to 61·5) per cent. SiO_2.

Dielectric Power Factor

As mentioned above, every insulator coming within the influence of an electric alternating field consumes a certain amount of electrical energy and transforms it into heat, and losses occur. The power factor of a dielectric is therefore a measure of the energy loss in an alternating field. In many applications of insulating materials it is important that the loss be as small as possible. In others the dielectric loss is not of importance as such, but its uniformity is a measure of the uniformity in manufacture. Porcelain insulators, which have a higher power factor than the normal one, have an unsound structure. In gases such as air under ordinary conditions, however, the losses are so small as to be practically negligible. Condensers with gases as dielectrics, e.g. air condensers, are used as loss free standards in power factor measurements. In solids the power factor ranges from 0·1 to 0·00001 in order of magnitude. The following table shows some

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typical values of power factor at room temperatures ;

	Power Factor at 60 ~	Power Factor at 10,000,000 ~
Wood Flour Filled Resin ..	0·04-0·3	0·035-0·1
Fabric Filled Resin ..	0·08-0·3	0·04-0·1
Asbestos Filled Resin ..	0·1-0·3	0·005-0·1
Laminated Phenol Resin..	—	0·02-0·8
Styrene	0·0003	0·0003
Cast Phenolic Resin ..	0·042	0·038-0·042
Porcelain	0·017	0·006
Steatite Normal	0.003	0·002
Steatite High Freq. ..	0·001	0·0001
Glass	0·03-0·0005	0·002-0·006
Mica	0·02-0·003	0·006-0·002

Since many noughts, especially in the figures for the low loss materials, are inconvenient to work with, the power factor is very often expressed in percentage or as power factor tan δ. For example, the power factor 0·0001 can be written as 0·01 per cent. or as tan $\delta = 1 \times 10^{-4}$.

Materials with slight porosity will show very different characteristics when measured in dry or in humid atmosphere ; but also in the case of dense and non-porous ceramic materials the influence of the surrounding air is of great importance owing to humidity films which may be formed on the surface.

Humidity control and exact records are, therefore, very essential. Fig 1 shows the variations of power factor of a steatite group material fired at varying temperatures : Curve A in a dry atmosphere of calcium chloride, and curve B in an atmosphere of 75 per cent. relative humidity (Robinson, *Journal I.E.E.*, November, 1940).

This material is dense when fired at 1,300° C., but more or less porous when fired at lower temperatures. If the material is dense, the values for the power factor obtained in both dry and 75 per cent. humid atmosphere lie close together.

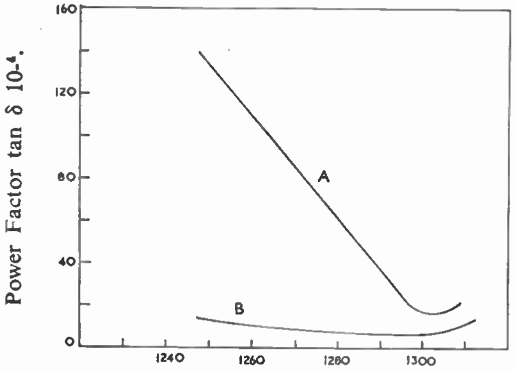

Fig. 1.—Variation of Power Factor of a Steatite Body with Varying Firing Temperatures.

These types of steatite bodies fired at lower temperatures are not dense but porous, and the lower the firing temperature the greater the porosity, and the higher the power factor if the measurement is taken in humid atmosphere. In a dry atmosphere both porous and dense materials have the same power factor.

Since as the rule insulating materials are not used in an atmosphere which is kept absolutely dry by calcium chloride or other moisture-absorbing chemicals, measurements taken in absolutely dry atmosphere give no indication of the usefulness of porous materials for practical service conditions. In tests for humidity the humidity may be maintained at any desired point by a reasonable airtight chamber in which a sulphuric acid/water containing mixture (of definite sulphuric acid/water ratio) is exposed to the air surrounding the specimen.

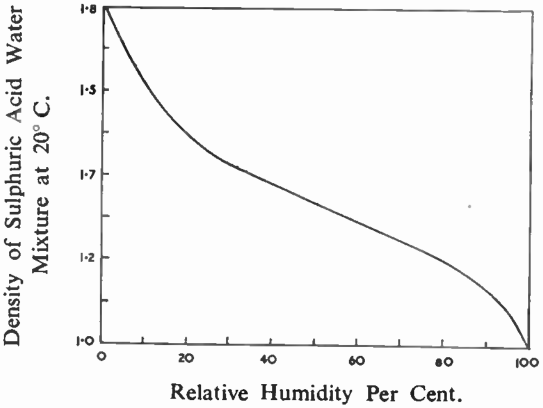

Fig. 2.—Relation of Relative Humidity of Air and Density of Acid-Water Mixture.

A desiccator can be used for a constant humidity chamber provided it can be kept where the temperature is constant. The dielectric properties, especially of porous materials, are affected considerably by temperature and humidity, and it is therefore of great importance that attention be paid not only to the test conditions at the time of measurement but also to the treatment undergone previous to the measurement.

All values giving the power factor of insulating materials should indicate the frequencies in cycles per second, temperature of the atmosphere in degrees, the percentage relative humidity of the atmosphere, and, in case of porous materials, the conditioning of the specimen.

Variation of Power Factor with Frequency

The variation of power factor of various materials with frequency is shown in Fig. 3, from which can be seen that all dense ceramic materials have a negative frequency coefficient, the frequency coefficient of the magnesium-orthotitanate bodies being negligible over a very wide range, the frequency dependency of the clinoenstatite and rutile group being almost negligible at radio frequency. Porcelain and feldspar containing steatite have a negative frequency dependence also, but the fact that the high power factor causes internal heating at radio frequencies makes the negative-frequency dependence a purely theoretical consideration.

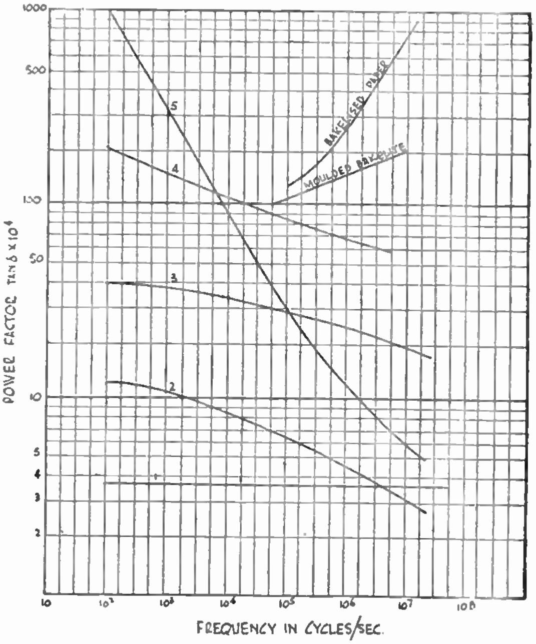

Fig. 3.—Variation of Power Factor with Frequency.

It is interesting to compare the amount of variation of power factor with frequency between some relatively well known and frequently used insulating materials. Measured over a frequency range of 1 kc. to 1 Mc/s. a true steatite dielectric exhibits a decrease in power factor from approximately 0·12 per cent. to 0·046 per cent., which is a gradual overall decrease of 0·074 per cent. power factor. Measured over the same range a steatite dielectric fluxed with feldspar starts off at 1 kc. with a 0·38 per cent. P. F. and drops to a 0·25 per cent. P.F. at 1 Mc/s., which is a gradual overall decrease of 0·13 per cent. P.F. A porcelain dielectric begins at 1 kc. with a 1·70 per cent. P.F. and drops to 0·7 per cent. P.F. at 1 Mc/s.

Any of these inorganic dielectrics shows a marked improvement of power factor with an increase in frequency, whereas the bakelite derivatives exhibit marked increase in power factor with a rise in frequency. If a component consisting of bakelised paper is not subjected to such a strong high frequency field—for instance, in the case of coilform—the disadvantages of the high power factor are, of course, not so conspicuous, especially at lower frequencies. The superiority of a ceramic coil-form (Curve A) with regard to the power factor compared with bakelised moulded material (Curve B) is extraordinary and specially marked at frequencies above 1 Mc/s. This is illustrated in Fig. 4.

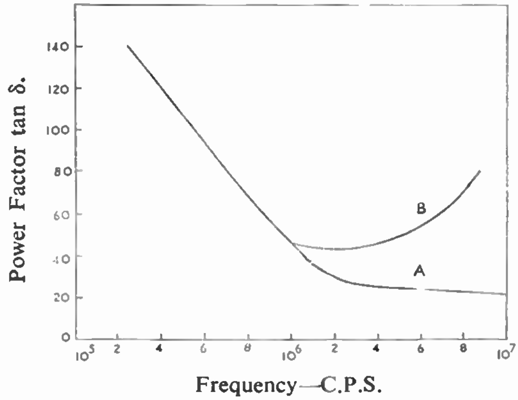

Fig. 4.—Variation of Power Factor with Frequency.

Similar conditions also prevail with regard to other components used in a high frequency field, and this is one of the reasons why high frequency ceramic materials should be used wherever such losses would otherwise occur. If the permittivity, or its temperature coefficient, is not of special importance, and if a low heat expansion is not required, the type of material most suitable is that of the steatite group.

Variation of Power Factor with Temperature

Temperature-power factor curves of various materials at high frequency (1 to 10 Mc/s.) present a means of comparing this type of dielectric behaviour.

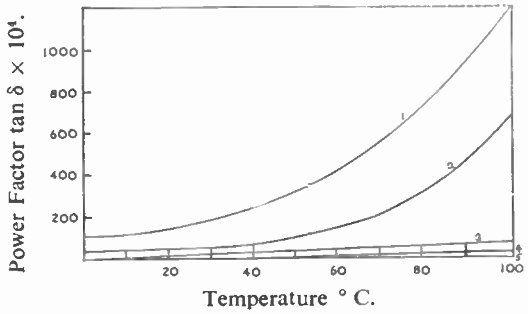

Fig. 5 (a).—Temperature-Power Factor Curves of Various Materials at High Frequency (1 to 10 Mc/s): (1) Porcelain, (2) Steatite containing Feldspar, (3) Rutile Body, (4) Steatite, (5) Magnesium-Orthotitanate Body.

In the above figures is shown the dependence of the power factor of various dense ceramic materials on varying temperatures between zero and 300° C. Porcelain (Curve 1 in Fig 5 (*a*)), having a room temperature per cent. power factor of 1·7, jumps to 12·0 per cent. P.F. at a temperature of 100° C. in a dry atmosphere.

A steatite fluxed with feldspar (Curve 2 in Fig 5 (*a*)) is not quite as bad, since it exhibits a rise of 0·38 per cent. P.F. to 6·0 per cent. P.F. over the same temperature scale. On the other hand, a true steatite dielectric (Curve 4 in Fig. 5 (*b*)) hardly changes its power factor between zero and 100° C. Between 100° C. and 300° C. the power factor rises only from 0·1 per cent. to 0·45 per cent.

This is a very important characteristic of these ceramic materials. Organic high frequency materials such as the so-called plastics cannot be used at elevated temperatures.

The conditions under which the power factor is measured, the shape of the test specimen and the shape of the electrodes and their application to the dielectric are of great importance,[1] and so is the nature of the surrounding media, the temperature and the frequency. The most important sources of discrepancies in the measurement of power factor are stray fields and poor contact of the electrodes and different humidity conditions of the surrounding air.

With regard to the electrodes, it is necessary to provide close contact with the specimen ; even small air pockets or interstices between the test specimen and the electrodes cause large errors in the measurement of the power factor. For testing ceramic materials the most convenient and most accurate method of applying the electrodes is to provide metal coatings on the surface of the test specimen by painting or brushing on precious metal-oxide solutions which after firing at about 750° C. form the electrode.

In the case of ceramic materials, the test specimen has the form of a disc 6 in. (15·24 cm.) in diameter. The thickness should not be less than 0·1 in. (0·25 cm.) and no more than 0·3 in. (0·762 cm.). The capacitance of a specimen should be not less than 10 $\mu\mu$F.

For frequencies above 1 Mc., the test specimens have to be smaller, and the diameter of the test disc for these frequencies is standardised by the A.S.T.M. as 2 in. (5·08 cm.).

It is very important that the thickness of the test specimens should be uniform with ± 5 per cent. of the normal thickness, and the surface has to be smooth and as free as possible of all irregularities.

Dielectric Strength

The dielectric or breakdown strength of an insulating material is that property which determines its suitability for use as a high tension insulator. The dielectric strength may be defined as the voltage gradient at which the electrical breakdown occurs. The dielectric strength of porcelain and other ceramic insulating materials—as well as that of all other solid insulating materials—is, to a very high degree, dependent upon the test conditions. It is calculated by dividing the breakdown voltage by the thickness of the test specimen between the electrodes and is commonly expressed in volts per mil or kilovolts per millimetre (1 volt per mil corresponds approximately to 40 volts per millimetre).

The test values for dielectric strength of an insulating material vary to an extent not generally appreciated with :

(1) The thickness of the material.
(2) The duration and rate of increase of the voltage applied.
(3) The characteristics of the voltage applied (frequency and wave shape).
(4) Electrostatic field distribution (edge effects, surrounding media).
(5) Temperature of the material.

In order to obtain comparable values for the breakdown characteristics of the dielectric, the conditions enumerated above must be exactly the same for all the materials tested.

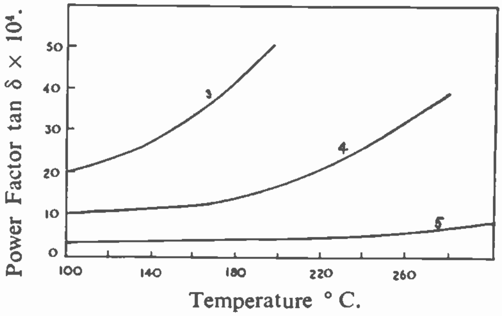

Fig. 5 (*b*).—*Curves* 3, 4 *and* 5 *have been extended on the Temperature Scale.*

Tests on specimens of different thicknesses, tests made with different electrodes, tests made with different rates of voltage increase, or in different surrounding media, are not comparable.

Variation of Dielectric Strength with Thickness of Specimen.

The thickness of the test specimen must be the same, at least within ± 10 per cent.

This is important, since in all cases of testing the same dielectric material with a variation in the thickness of the discs the dielectric breakdown voltage per mil thickness was found to increase with a decrease in thickness of the test specimen. True steatite normally exhibits a breakdown strength of 200 volts/mil for a 0·3 in. thickness with, on one hand, a breakdown voltage of 400 volts/mil for a 0·1 in. thickness, and, on the other hand, a reading of 130 volts/mil for 0·7 in. specimen.

The breakdown voltage is effected by the surrounding media owing to edge effects caused by surrounding media having higher breakdown strength and lower dielectric constant than the test specimen.

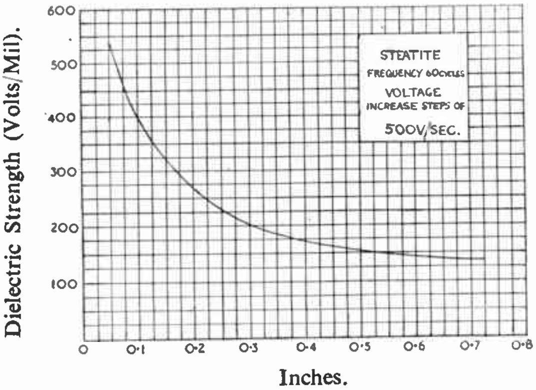

Fig. 6.

Variation of Dielectric Strength with Temperature

Temperature affects the breakdown voltage to a large extent.

The dielectric strength of a true steatite dielectric which starts off with a puncture of 580 volts/mil at ambient will fall to 570 volts/mil for a specimen of the same thickness at 100° C. Then a sharper drop occurs until measured at 250° C., the puncture will occur at 480 volts/mil. The influence of power factor on the thermal breakdown strength, particularly at elevated temperature, is also illustrated on the same curve.

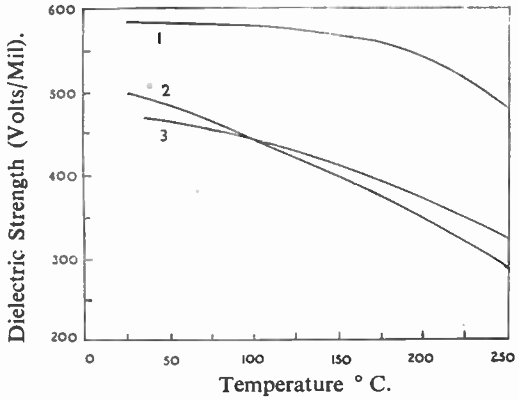

Fig. 7.—*Dependence of Breakdown Strength of* 3 *Steatite Materials on Temperature.*

(1) *Alsimag* 196 (*power factor* 0·14 *per cent. at* 60 *cycles*).
(2) *Alsimag* 35 (*power factor* 0·30 *per cent. at* 60 *cycles*).
(3) *Alsimag* 197 (*power factor* 0·20 *per cent. at* 60 *cycles*).

The decrease in dielectric strength between ambient and 250° C. is only about 15 per cent. in the case of the specimen with the lowest power factor, and this small decrease is due to the lower power factor and high volume resistance at elevated temperatures of this special material. Breakdown strength at temperatures higher than 80° C. is, generally speaking, better, the higher the volume resistivity at elevated temperatures and the worse the power factor of the material under test.

After seeing how the power factor influences dielectric strength, let us compare power factor and dielectric strength of several other dielectrics.

	P.F. 1,000 kc/s Per cent.	Puncture 60 cycles Volts/Mil
Steatite	0·120	200
Porcelain	1·70	120
Glass-bound Mica..	0·19	150
Quartz Glass ..	0·003	400

In order to form an idea as to why the dielectric strength of solid insulating materials decreases with increasing thickness, it may be as well to discuss at this stage the theory of breakdown of solid materials.

Theory of Breakdown

Dielectric failure of solid insulating materials may occur in one of the following ways, or in a combination of both :

(*a*) In disruptive breakdown ;

(*b*) In thermal breakdown.

Disruptive failure is one which results directly from an electrical overstress of the dielectric material without perceptible internal temperature rise. It is caused by ionisation and collision within the molecular structure of the material.

Disruptive failure occurs in the case of solid insulating material only under special conditions, and accurate test values of pure disruptive dielectric strength for such materials are not easily obtained. If tests are made on very thin specimens so that heat may easily be dissipated by the electrodes and a sufficiently high voltage is applied to cause instantaneous breakdown, that there is no time for heat to develop in the thin section, the failure is purely disruptive. Impulse tests on thin ceramic sections cause a breakdown which is predominantly, or almost purely, disruptive.

With increasing thickness internal temperature effects modify the characteristics of disruptive failure. The breakdown strength per unit wall thickness at first decreases slowly with increasing wall thickness and then more rapidly when a certain wall thickness is reached, the breakdown showing more and more the characteristics of thermal breakdown with increasing wall thickness. Heat developed under the influence of the alternating electric field between the electrodes can less easily be dissipated when the wall thickness increases. When a certain thickness of the specimen is reached, a further increase in wall thickness will then no longer result in an increase of breakdown voltage. This critical wall thickness, an increase of which would not cause a further increase in breakdown voltage, depends not only on the dielectric properties of the test specimen but also on the nature of the surrounding medium. Theoretically, the disruptive breakdown voltage is proportional to the thickness of the test specimen (E. B. Shand, "Dielectric Strength of Glasses," *El. Eng. Trans.*, August, 1941). For commercial frequencies and for thickness such as are used in actual insulator design, disruptive breakdown is the smaller and thermal breakdown the larger of the two components causing the actual breakdown. Disruptive breakdown strength is the higher the more homogeneous the structure of the insulating materials. Thermal breakdown strength is determined by:

(1) Electrical conductivity (reciprocal of volume resistivity).

(2) Thermal conductivity.

(3) Power Factor.

(4) Dielectric constant of the insulating material (specific inductive capacity, or permittivity).

The higher the dielectric constant and the higher the power factor of the test specimen, the higher will be the electrical losses and more heat will be developed. The heat developed reduces the volume resistance of the material and more current will develop further heat until breakdown occurs. It is well known that every insulator coming within the influence of an electric alternating field consumes a certain amount of electric energy and transforms it into heat. The electrical energy lost in this way is given nearly enough by the following equation.

$$N = V^2 2 \pi f C \tan \delta$$

where V is the voltage

f the frequency

C the capacity of the test specimen

tan δ the tangent of the loss angle, or the power factor of the insulating material.

Since increased energy loss means increased heat generated, it can be concluded from this formula that insulating materials having a higher power factor possess a lower dielectric breakdown strength, particularly at high frequencies, and if the voltage is applied for a long period, or increased at a small rate, i.e. if the thermal component of the actual breakdown is predominant. The disruptive breakdown, however, seems to be less dependent on the power factor.

The curves (Fig. 7) illustrating the influence of temperature on the breakdown strength of three steatite materials also show the influence of power factor on the thermal breakdown strength, particularly at elevated temperatures.

Although the phenomena causing breakdown cannot be attributed exclusively to the the two factors "disruptive" and "thermal" breakdown, there is no doubt that these are the two most important factors and that breakdowns which occur in practice are in most cases the result of these two factors.

Short-time (or impulse) tests are predominantly disruptive in their nature and long-time tests, high frequency tests and tests at elevated temperatures are predominantly thermal. In most cases, disruptive and thermal effects combine to produce failure. If the breakdown is purely disruptive the breakdown current increases from a substantial steady value to breakdown in a fraction of a microsecond.

Volume and Surface Resistivity

The "resistivity" is that property of an insulating material which determines its suitability for use as an insulator. If the volume resistivity of material is less than 1 megohm/cm³ it may, in accordance with the A.S.T.M. Standards on Electrical Insulating Materials, normally not be considered as an insulating material. Resistivities of ceramic dielectrics are, however, very much higher than the above quoted minimum.

Approximate values of volume resistivity of some insulating materials are:

TABLE 2

Volume Resistivity of 25° C. American (A.S.T.M.) Standards

	MΩ/cm³
Ivory	2×10^2
Celluloid	2×10^4
Marble	1×10^5
Plate Glass	2×10^7
Amber	5×10^{10}
Fused Quartz	5×10^{12}
Ceresine	75×10^{12}
	Ω/cm³
Steatite	71×10^{14}
Porcelain	71×10^{19}
Quartz Glass	1×10^{19}

Current can pass either through an insulator or across the surface layer, or both ways.

"Volume resistivity" is the resistance between two electrodes covering opposite faces of a centimetre cube, if no current flows through the surface layers. "Surface resistivity" (of a unit face) is four times the resistance between two electrodes covering opposite faces of a centimetre cube when all the current flows through the surface layer.

"Surface resistivity" of a material is, therefore, determined by the film of water, oil or other liquid deposited on the surface of the insulating material. The surface resistivity is thus dependent on the thickness of the film and on its nature. The quality of the

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surface determines to a great extent the surface resistivity since smooth surfaces hold less humidity than rough ones.

A material which has high volume resistivity has not necessarily high surface resistivity. By glazing, by grinding or by polishing the surface of a ceramic article it may be made more smooth and the capacity of its surface to hold a skin of liquid thus reduced. The surface resistivity is consequently increased.

The surface resistivity of some common solid insulators may be given hereunder (taken from A.S.T.M. Standards) :

TABLE 3

	Surface Resistivity at 25% Rel. Humid.	MΩ/cm^2 at 90% Rel. Humid.
Ivory	10^4	50
Celluloid	10^5	10^3
Marble	10^5	10
Plate Glass	10^8	20
Amber	10^9	10^5
Fused Quartz	10^9	10^2
Ceresine	10^{11}	10^{11}

The surfaces of ceramic materials in humid climates have the disadvantage of having moisture readily condensed on them. In most cases these insulators have smooth surfaces resulting from their method of manufacture and often this surface has been glazed to aid in their being easily cleaned by water falling on them, as rain or by manual periodic cleaning. This surface, however, does not prevent, and in fact, being smooth, aids in the spread of liquids condensed upon it. Let us visualise two examples: first, an insulator used on a ship at sea may be splashed by a wave, or, secondly, an insulator in use in the jungle may receive dew when the temperature falls at night time. There may not be sufficient air circulation to evaporate the liquid and it spreads into a film over the insulator. Surface resistivity is lowered and flash-over may more easily occur, and in addition, in the first case, the layer of salt upon evaporation crystallises and becomes a rough layer covering the originally smooth surface and when the next splash is received the rough surface allows a thicker film of liquid to build up and present a much greater chance for flash-over. To prevent the liquid from spreading over the surface in a conductive film the surface is often treated before or after assembly with a coating of an organic material, which, not having an affinity for water, causes the water to bead up and never allow a continuous conducting film to form. However, it is believed that up to date there has been no method developed of treating the surface to provide a permanent truly anti-wetting surface.

A question may be rasied here as to why should ceramic insulators be used in the above cases when other materials, such as the plastics group, do not, in all instances encourage to the same extent, due to their relative specific heats, the condensing of vapours upon them. In answer to this question several facts should be remembered. Firstly, the ceramic is a rigid insulator, that does not deteriorate with moisture of any nature, in fact, the steatite insulators are resistant to all acids except hydrofluoric acid. Secondly, the volume resistivity is so high that the voltage gradient from inside to the surface of well designed insulators is so great that little cause for surface leakage is present. Thirdly, the dense ceramic will not permit the passage of any liquid or gas notwithstanding the length of time immersed. Fourthly, in the two cases visualised above the insulator may be subjected during the less humid part of the day to an atmospheric temperature high enough to bring about the dielectric breakdown of any other than the ceramic class of dielectric. The fourth advantage to the use is that ceramic materials are the hardest materials yet in use as dielectrics which prevent deterioration of the surface and body over a wider range of abuse than any other type of insulation.

Mechanical Characteristics of Ceramic Materials

The impact strength is the relative toughness of materials as indicated by the energy used in breaking a standard test specimen in one blow. In the table below is given the impact strengths of several widely used insulating materials :

TABLE 4

Impact Strength

Porcelain	0·84 - 0·98 ft. lbs./in.^{2}
Steatite	1·3 - 2·3 ft. lbs./in.^{2}
Mycalex	1·5 - 2·8 ft. lbs./in.^{2}
Phenolic resin wood filled	0·3 - 0·5 ft. lbs./in.^{2}
Laminated Phenolic Paper filled	0·3 - 3·8 ft. lbs./in.^{2}

The tensile strength of a material may be defined as the number of pounds or kilos pull per square inch or square centimetre required to break the specimen. It is obtained by dividing the total load required to break the specimen by the area of cross section of the specimen at the point where the break occurs.

When a specimen has been tensile-tested to destruction, the fracture should show the entire cross-sectional area to consist of a very coarse granular surface. If the specimen is not completely subjected to a pure tensile test, and compression and bending are partially introduced, the surface is then divided into distinct areas—the area of tension and the area of shear (the latter being much more smooth). The tensile strength of a ceramic test specimen is affected by the type of glaze employed. The glaze may decrease or increase the mechanical characteristics. The use of a glaze having an appropriate coefficient of thermal expansion increases the tensile strength very considerably.

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TABLE 5

A few Tensile Strength Values :

Porcelain (Glazed)	4·26 - 7·10	lbs./in.$^2\times10^3$
Porecelain (Unglazed)	3·41 - 4·54	lbs./in.$^2\times10^3$
Steatite	7·5 - 10·0	lbs./in.$^2\times10^3$
Mycalex	6·6 - 7·3	lbs./in.$^2\times10^3$
Phenolic resin wood filled	4·0 - 11·0	lbs./in.$^2\times10^3$
Laminated phenolic paper filled	7·0 - 18·0	lbs./in.$^2\times10^3$
Polystyrene	3·0 - 6·0	lb.s/in.$^2\times10^3$

Compressive Strength

The compressive strength of ceramic insulating materials is very high. It is not easy to obtain very uniform results on test since initial failures occur before the ultimate compressive breakdown strength has been reached, owing to the fact that it is very difficult to get the flat surface of the test specimen absolutely smooth and parallel. Variations in test results, due to variation in composition, are not so marked as in the case of impact, tensile, and flexural strength tests.

Since the compressive strength is high, designers of ceramic insulators design them in such a way that they are mainly subjected to compressive stresses in all cases where very high mechanical characteristics are required and where, at the same time, the dimensions have to be kept small.

TABLE 6

Compressive Strength

Porcelain	39·8—65·5	lbs./in.$^2\times10^3$
Steatite	75·0—85·0	lbs./in.$^2\times10^3$
Bakelite	12·0—28·4	lbs./in.$^2\times10^3$
Polystyrene	14·0	lbs./in.$^2\times10^3$

Flexural Strength (Modulus of Rupture)

The flexural strength of ceramic materials changes roughly in direct proportion to the tensile strength, but the influence of body and manufacturing modifications is, as a rule, more clearly shown by tensile strength tests.

As an average the modulus of rupture is somewhat more than twice the tensile strength, as far as dense ceramic materials are concerned and can be three times the tensile strength in the case of porous ceramic materials.

The following table gives the flexural strength of some of the dielectric materials :

TABLE 7

Flexural Strength

Porcelain (Glazed)	12·8—14·2	lbs./sq. in.$\times10^3$
Porcelain (Unglazed)	5·7—11·3	lbs./sq. in.$\times10^3$
Steatite	18·0—22·0	lbs./sq. in.$\times10^3$
Mycalex	14·0	lbs./sq. in.$\times10^3$
Fused Silica	9·0	lbs./sq. in.$\times10^3$
Porous talc bodies	11·3—12·8	lbs./sq. in.$\times10^3$

Temperature Shock Tests

In the case of tests on finished insulators, it is laid down in American specifications that each insulator has to undergo 10 complete temperature cycles, immersed first in a cold water bath at 0° C for ten minutes and then transferred quickly to a hot water bath at 100° C., remain there 10 minutes, then put back into the cold bath. All properly compounded ceramic insulators will stand this test.

The resistance to temperature change is the greater the lower the thermal expansion and the larger the thermal conductivity of the material.

The type of glaze applied to the ceramic bodies has a direct bearing on the resistance to thermal change.

If the glaze has a greater heat expansion than that of the body to which it is applied when both are cooling down, the glaze has a tendency to assume a smaller area than the surface area of the body. The glaze, although sticking firmly to the body, is subjected to a tensile stress. This tension may cause rupture of the glaze either during cooling or later on in service as the result of some external cause. This breaking usually takes the form of numerous cracks and is generally known as " crazing."

If the glaze has a lower heat expansion than that of the body, it has a tendency to assume a greater area than the surface area of the body. The glaze is then held in a state of compression. Under excess compressional stress the glaze will tend to be pressed away from the body and result in " chipping " or " peeling " of the glaze.

For best results in thermal shock tests the glaze should be in slight compression rather than in tension. Provided the glaze has the proper pyrochemical bonding the very thin layer of glaze will exert enough bonding strength to the body to enable it to pass heat shock tests that the body could not stand without its help.

Porosity

Ceramic materials used as insulators have, as a rule, to be vitrified and non-porous. For other technical applications and in the case of insulators used at very high temperature, the materials may be slightly porous. There are even applications where a certain porosity is required. When the porosity exceeds 20 per cent., the exhausting of vacuum tubes is accelerated due to the fact that the gas can be pumped from the spacer material without heat treatment. Insulators which have a vitreous vesicular structure are sources of future trouble in a tube, due to the possibility of the thin walls collapsing under stress of bombardment and releasing the enclosed gas into the tube envelope. For this reason, it has been considered advisable to use extremely porous spacers rather than those which are highly vitreous.

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A.S.T.M. Standards Method of Testing Electrical Porcelain (D116-42) Dye Penetration

42. *Apparatus.*—The apparatus shall consist of a suitable pressure chamber of such dimensions as to accommodate the test specimen when immersed in the dye solution with arrangements for obtaining and maintaining the required pressure for the required time.

43. *Reagent : Fuchsine Solution.*—A solution consisting of 1 gr. of basic fuchsine in 1 litre of 50 per cent. alcohol is suitable. If a denatured alcohol is used, one should be selected which does not react with the dye to cause fading of the colour.

44. *Test Specimens.*—The test specimens shall be freshly broken fragments of the porcelain body, having clean and apparently unshattered surfaces exposed. At least 75 per cent. of the area of such specimens should be free from glaze or other surface treatment. Fragments approximately ¼ in. in the smallest dimension up to ¾ in. in the largest dimensions are recommended.

45. *Procedure.*—(*a*) The test specimens shall be placed in the pressure chamber and completely immersed in the fuchsine solution.

(*b*) A pressure of approximately 4,000 p.s.i. ± 10 per cent. shall be applied for approximately 5 hours or an optional pressure of 10,000 p.s.i. ± 10 per cent. for 6 hours may be used.

(*c*) At the conclusion of the application of test pressure, the specimen shall be removed from the pressure chamber, thoroughly dried, and broken as soon as possible for visual examination.

(*d*) Porosity is indicated by penetration of the dye into the porcelain body to an extent visible to the unaided eye. Penetration into small fissures formed in preparing the test specimen shall be disregarded.

46. *Report.*—The report shall include a statement of the observations recorded in accordance with the examination prescribed in Section 45 (*d*).

Tentative revision, submitted June, 1942.

For relatively coarse and porous bodies (0·1 per cent. absorption and over). The amount of water which they absorb is measured and the porosity is expressed as a percentage by weight of the water absorbed. The specimen is first weighed (after having been dried at a temperature of 120° C. and cooled in a desiccator). The specimen is then boiled in water for one hour and weighed again after the surface water has been wiped off with a cloth. The difference between the weight in dry state and after immersion in boiling water gives the weight of the water absorption.

Some Notes on Die Pressed Ceramics

To form the simplest article, the die consists of a stationary block, or die case, with a movable top and bottom punch. A solid article, round or square, in cross section, as the requirements may be, needs these three parts. If holes are required stationary pins are added running up through the bottom punch and into the top punch. If several steps in thickness are required in an article this necessitates moving parts within the bottom punch to distribute the pressure evenly to the various thicknesses. The cross section of the die case and the punches are shaped to the design required by the customer, allowing for the shrinkage of the body in the firing operation. The finest die steels are used and the various die parts are machined and polished to a high degree of accuracy.

A few suggestions to the prospective purchaser of die pressed insulators may aid in the intelligent design of the ceramic part and enable it to be manufactured more economically, effecting smaller production losses, and thus making possible lower selling prices.

(1) Give the ceramic supplier full information as to the size of parts that fit into or around the ceramic. Whenever possible, the supplier should be furnished with a sample assembly so that the economical design may be checked. Usually the metal stamping dies are cheaper than the steatite-pressing dies and can be altered more easily.

(2) Always allow as liberal tolerances as possible. It may seem paradoxical that the ceramic manufacturer boasts of his ability to hold exacting tolerances and then ask for broad tolerances, but it reduces to this : the supplier can furnish ceramics to close tolerances, but when they are more restrictive than ordinary commercial tolerances, he must resort to costly individual gauging.

(3) Bevelled edges are very helpful. As the die parts wear, the material crowds into the resulting crevice between punch and block and forms a fin or flash on the ceramic. Where a bevel is allowed the supplier will profile his punch faces and the ceramic will be neater and the dies last longer.

(4) Bosses, counterbores or depressions should be kept as low or shallow as possible and their walls should be tapered about three degrees.

(5) The number of different levels should be kept at a minimum.

(6) Wall thickness between the edge of the ceramic and holes or depressions should be as substantial as possible, else cracks will have a tendency to result.

(7) Avoid very small pins, and all designs that necessitate dies of weak construction.

(8) Holes can only be pressed-in when parallel to the axis of pressing. Other holes must be drilled into the article individually after pressing.

(9) Pressed ceramics should not be too long in direction of pressing. They will have a tendency to have a centre section smaller than the ends.

(10) Thin sections, no matter where, should be avoided. They tend to crack, warp, or blister, thus making the ceramic hard to control.

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(11) Bosses should be used wherever flat, ground, parallel surfaces are required, thus keeping the ground area at a minimum.

(12) Threads of tapped holes cannot be pressed in. Unless special binders are used the pressed ceramic crumbles to some extent in the tapping operation, especially with fine pitches, so as large and coarse a thread as possible should be chosen. If the screw must enter the ceramic quite a distance, it would be advisable to counterbore a fraction of the hole so that any variation in firing shrinkage and its accompanying variation in pitch will still allow the screw to enter. Holes tapped into a ceramic perpendicular to the pressing axis will invariably fire out oval shaped.

In conclusion it may be requested that the radio parts and electrical appliance manufacturer designs his ceramic with an eye on the probable shape of the die that it will need. In all cases consult the ceramic manufacturer before deciding on the final design, and this consultation will normally result in shorter delivery time and less headaches for all involved.

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BROADCASTING IN EUROPE

(A summary of the discussion meetings held by the London, Midland, North-Western and Scottish Sections of the Institution in October, 1945, *and based on the report issued by the Radio Industry Council in July,* 1945*)

The Chairman (Mr. L. Grinstead): To-night we are to have a discussion on a topic which is of lasting interest to radio engineers, that of frequency allocation for broadcasting stations. This subject is, at the moment, of more than usual interest and importance, for it is closely connected with many phases of post-war planning. I think it will be agreed that a new plan for broadcasting is most desirable, because present arrangements do not permit satisfactory coverage throughout Europe. A very large proportion of broadcast listeners receive sound programmes which are limited in their audio frequency range and, in addition, are marred by interference from stations working on adjacent channels. Further, reception is often seriously affected by fading.

The Radio Industry Council has been courageous, in my opinion, in presenting a plan for better European reception, and is entitled to our full co-operation in its efforts to improve matters in the field of broadcasting. Many members will have studied the R.I.C. plan which we are to discuss to-night, and I would ask speakers to observe the importance of contributing constructive remarks in order that our co-operation may be useful to the authors of the plan. We must carefully examine all aspects of the plan, as it would be of little help if, in our enthusiasm, we were to decide immediately that the plan proposed is the only one possible.

Naturally, the scheme would take some years to bring into full operation, and involve very considerable work and expenditure by the broadcasting organisations and the radio manufacturers of Europe. Any such plan must, therefore, finally be assured of success before it is put into operation.

We are fortunate to have with us to-night to open our discussion one of the authors of the R.I.C. plan, Mr. R. G. Clark. I hope he will have gathered from these preliminary remarks that our discussion to-night is intended to be helpful and constructive, and it is in this spirit that I ask you to extend our usual welcome to our visitor.

Mr. R. G. Clark: In the following remarks, I shall discuss a number of aspects of European broadcasting only lightly dealt with in the published plan, and I shall endeavour to provide additional information on certain matters which it is hoped will clarify the published material.

To discuss this matter intelligently, it is necessary to review briefly the history of broadcasting in Europe and to note certain significant changes which have taken place in the last twenty years.

At the commencement of organised broadcasting, low power transmitters generating radio frequency powers of the order of 1 kW were universal. In addition, it was frequently the case that these were used to energise very indifferent antennæ. With such transmitters, the problem of frequency allocation was largely one of squeezing the maximum number of channels into the available spectrum and this was at least a partial cause of the standardisation of a 9 kc/s separation between channels. In addition, programme practice has changed enormously. In the early days, regional programmes were practically universal, the linking of transmitters by land lines for broadcasting important events being an exceptional practice. However, with the introduction of more ambitious programmes, in which the cost of the programme material enormously outweighed the cost of transmission, this situation has completely changed and, at the present time, the national distribution of programmes is a universal practice, regional programmes being used to satisfy local cultural requirements only.

Reverting to the improvements which have taken place in transmitters, it is nowadays common practice, of course, to use medium and long-wave transmitters radiating power of the order of hundreds of kilowatts. In addition, antennæ have been the subject of a good deal of study and considerable improvements have been effected in the control of high angle radiation by the use of the $\frac{5}{8}\lambda$ aerial. Additionally, some advantage has been obtained by the use of more complex systems controlling radiation in the azimuth in order to minimise interference problems at long ranges. With this improved technique at our disposal, and with the contemporary improvement in receivers, it may fairly be stated that the range of broadcasting stations is defined by those conditions which control the onset of fading. The definition of range in this way is by no means exact. Authorities who have studied the question show considerable divergences of opinion in several respects.

Fig 1 illustrates how the rather arbitrary $\frac{\lambda}{4}$ factor

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*Copies of the report are available to members on application to the Institution

(In order to avoid duplication of contributions, all section reports have been edited).

compares with the conclusions arrived at by various authorities. So very simple a formula can only be a first approximation at best, but we cannot hope to do better than this without a detailed study of every individual case, which is outside the scope of the present examination of the problem, owing to the considerable variations in soil conductivity experienced in different parts of Europe and of every country. The figure of 10^{-13} adopted represents a fair average for Europe, but the limits are approximately 10^{-12} and 10^{-14} e.m.u. Due to the manner in which the ground-wave attenuation is related to conductivity, this means that the range varies approximately 10 : 1 within these limits of conductivity, i.e., 3 : 1 either side of the mean values shown on the slide.

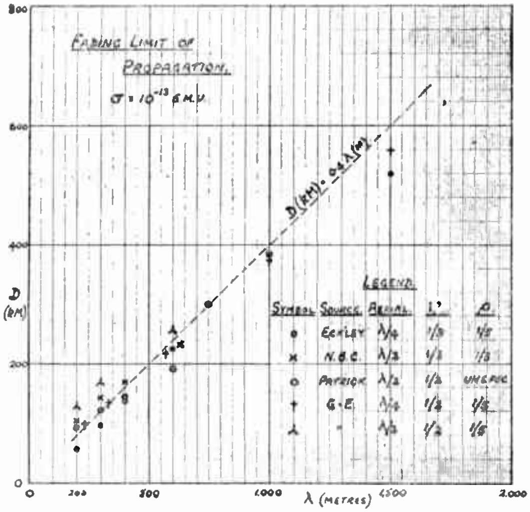

Fig. 1.

Before proceeding to a discussion of the plan adopted, it is perhaps worth while to emphasise the importance of long-wave transmission. Whatever expression is adopted to define the range of a transmitter in relation to frequency, there is no doubt as to the superiority of long waves in this respect. It is true that the early long-wave transmitters were only partially successful, since very high power is necessary to overcome the high ambient electrical noise level in urban surroundings. However, powers in the order of 1,000 kW or more are now entirely practicable in such transmitters and, indeed, such stations exist. (It may be remarked that the development of high power industrial electronic gear may be useful in this connection by making available transmitting valves and other components suitable for still higher powers.)

In considering the plan itself, Appendix II contains a table illustrating the approximate order of wave lengths required to cover satisfactorily the various European countries. It is found that fourteen countries require long waves, counting European Russia as two countries for the purpose of these allocations. It is considered that a certain amount of frequency sharing will be practicable between widely spaced transmitters—this practice already having been adopted in certain instances. With this expedient, we find that twenty-two frequencies are required in the long-wave band and these extend from 156-288 kc/s and from 344-432 kc/s. In connection with this extension of the long-wave band, it is worth while drawing attention to the fact that the Montreux Plan permitted broadcasting stations of by no means negligible power in this band. Including side-bands, the following spectra approximately were envisaged :—

340—360 kc/s.
380—400 kc/s.
410—450 kc/s.

It is recognised that this scheme could only be operated in agreement with other authorities, but there seems to be no valid reason why the same methods should not be applied to the proposed plan.

At this point, it is perhaps as well to make it clear that the choice of 11 kc/s separation proposed is a result of trial and error. Ideally, we feel that a greater space than this is desirable, but the choice is a difficult one, in which many compromises have to be made, and, in our view, 11 kc/s is the best separation taking all factors into account.

Turning to national allocations in the medium-wave band, we find that with 11 kc/s separation, 92 channels are available in this band. Of these, national services occupy 41 frequencies, including some provision for extra-European stations, e.g., North Africa, which have to be considered since they are potential sources of interference in some parts of Europe. Turning next to the regional scheme, the allocations already made in the medium wave-band leave for the regional transmitters 17 frequencies below 1,000 kc/s and 38 above this frequency. Allowing only one station per channel below 1,000 kc/s and only two stations per channel above 1,000 kc/s, this provides us with 93 channels. This figure happens to coincide exactly with that given in Appendix 5—Suggested Regional Services.

It appears to be indicated from past practice that it will be quite acceptable if all Russian regional transmitters share frequencies with similar stations in Western Europe.

It is, of course, recognised that no scheme of allocation and distribution will overcome dead spot difficulties in certain areas due to bad propagation conditions, and there seems to be no reason to deviate from past practice in the matter of providing a number of low power stations to fill up any such gaps. In this connection, it is interesting to cite some of the provisions of the Montreux Plan ; for example, International Common Waves, Type I, are allocated 1,366 kc/s—no less than 23 transmitters being visualised on this frequency, and 1,438 kc/s—with 19 transmitters.

In conclusion, it is desired to emphasise that the purpose of this plan is to provide the maximum amount of good broadcasting for most of the people, most of the time, which appears to be the right ideal at which to aim. The solution put forward does not claim to be unique in any respect. With so many variables, the unique and perfect solution is impossible, but it is felt that this plan makes out a case for a better solution than that reached by 1939, when political consideration so frequently overshadowed engineering matters in the distribution of broadcasting.

The sponsors of this plan feel that it will have served its purpose if it promotes discussion leading eventually to a better compromise than has existed in the past.

Finally, I would like to say that the Radio Industry Council appreciates the facilities given it by this Institution to publicise this proposal and that the sponsors of the plan look forward to a full and constructive discussion and criticism.

Mr. P. Adorian : The main point of criticism that I will submit is that the service range of broadcast transmitters, as assumed in the report, can in fact not be attained.

There are also other points of criticism, such as use of shared wavelengths ; the availability of channels due to requirements of other services ; and insufficient allowance for national requirements. I propose to deal in some detail with the first and second points, but only refer briefly to the other points, as I believe others will deal with these in full.

Service Area, Theoretical Examination

In arriving at a figure for the service area of a broadcasting station, the R.I.C. plan specifies a minimum signal greater than 2 millivolts per metre ; it assumes an average soil conductivity of 10^{-13} e.m.u. and, taking the tolerable ratio of space to ground ray as 1 to 3, the report gives

$$\text{Range (miles)} = \frac{\lambda \text{ metres}}{4}$$

While it is appreciated that this is only meant as an approximation, in my opinion, it is a very optimistic approximation and in the following considerations it is proposed to show this and arrive at an expression which is a closer and truer approximation.

It is not possible to accept the R.I.C.'s plan figure of space to ground wave of 1 : 3, as this in itself does not mean very nuch.

While the ground wave stays reasonably constant, the space wave varies considerably, and the C.C.I.R. has defined as " quasi-maximum " value of the field due to space wave, the value which is exceeded during 5 per cent. of the time.

Thus, if the quasi-maximum value of the field for a certain station for a certain point is 3 millivolts/metre, this means that 5 per cent. of the time, the field due to the space wave at that point exceeds 3 millivolts/metre. If at this same point the field due to the ground wave is 3 millivolts/metre, it is evident from the foregoing that 5 per cent. of the time the field due to the space wave will equal or exceed that due to the ground wave. The vectorial sum of these two fields will vary between zero and 6 millivolts + and would result in very bad distortion indeed, mainly due to what is known as selective fading, as at some frequencies within the sidebands, the vectorial sum of the ground and space wave may subtract while at others they may be additive. (Incidentally, the space wave field reaches about ⅓ the quasi-maximum value about 50 per cent. of the time.)

These conditions apply during night-time, as during day-time there is very little space wave and thus the transmitter service area is greater in the day-time. As maximum listening probably occurs during night-time, it is necessary to design for conditions when space waves are present.

The following table shows the field intensity of ground waves at various distances for soil conductivity of 10^{-13} e.m.u. for a radiated power of 1 kilowatt. (For other radiated powers, P kW, multiply these figures by $\sqrt{P}$.) Graphs are included for wavelengths between 200 and 2,000 metres up to distances of 400 miles (these values were published by C.C.I.R. in 1937). On the same figure the quasi-maximum values of space field are included as a dotted line (and the values in this case are those

GROUND WAVE INTENSITY FOR WANTED STATIONS
and
SPACE WAVE INTENSITY FOR UNWANTED STATIONS ON SHARED WAVELENGTHS ACCORDING TO APPENDIX 111 OF R.I.C. PLAN

Power of all Transmitters assumed 1 Kilowatt
(for higher values of P multiply field strength by $\sqrt{P}$).
Average soil conductivity assumed 10^{-13} e.m.u.

Frequency (kc/s)	Country	R.I.C. Plan Service Range (miles)	Ground Wave Intensity of Wanted Station at edge of Service Area (micro-volts/(metre	Distance between edge of Service Area and Unwanted Station working on same frequency (miles)	Space Wave Intensity of Unwanted Station at edge of Service Area of Wanted Station (micro-volts/metre)
156	Iceland Russia	500	70	1700	10
211	Iceland Russia	380	110	1800	9
244	Spain Russia	300	120	1500	15
355	Spain Russia	210	150	1600	12
388	Finland Turkey	190	200	1400	17
421	Finland Turkey	180	200	1400	17

published by the F.C.C. in 1935). They correspond to space fields for a 1 kilowatt transmitter. (The same remarks as before apply for other powers at the transmitter.)

From this table we can now construct graphs which show the service range of broadcast transmitters of different wavelengths. In Fig. 2, graph A, the service range of broadcast transmitters is shown if the ratio of the quasi-maximum value of the space wave to ground wave field is taken as I : 1. Graph B shows a similar curve, but for the ratio of 1 : 2 and graph C 1 : 3. The straight line on the same figure corresponds to the $\frac{\lambda}{4}$ value.

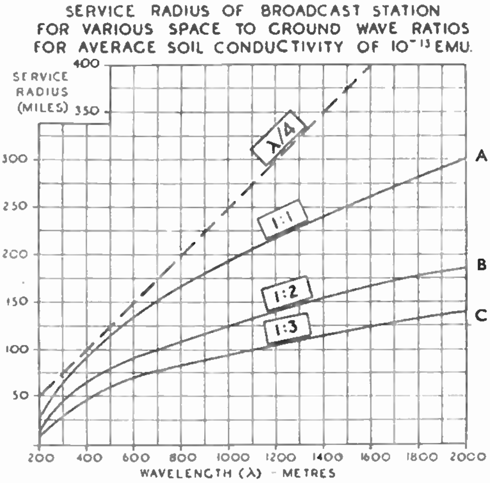

Fig. 2.

It is quite easy for anybody to satisfy himself after quite simple listening tests that when conditions are such that the field strength due to the ground wave is equal to the quasi-maximum value of the space field, the quality of reproduction becomes so poor, due to selective fading, that such a location cannot be considered within the service area.

It will be seen that even this graph (Fig. 2, A), which I maintain is not acceptable, shows a considerably lower service range than that assumed in the R.I.C. plan.

Service Area, Practical Tests

Having stated that even the service range given by Fig. 2 A is too high, it then becomes a question of reasonable judgment, and to some extent compromise, to decide what is an acceptable figure. In my opinion. Fig. 2 B closely approximates such a value, but owing to the numerous variables and varying conditions, it is somewhat difficult to establish with any great accuracy what is the correct expression for service range for wavelengths between 200 and 2,000 metres.

Fig. 3 shows a curve which has been obtained as the result of observations over a considerable period of years on different wavelengths between 200 and 500 metres and on 1,500 metres. The other figures have then been interpolated.

It so happens that the equation for this particular graph is :

$$\text{Range (miles)} = 1{\cdot}3 \times \lambda^{\frac{2}{3}} \text{ metres,}$$

which is about the same as

$$\text{Range (miles)} = \frac{\lambda}{8} \text{ metres} + 20.$$

between 200 and 2,000 metres.

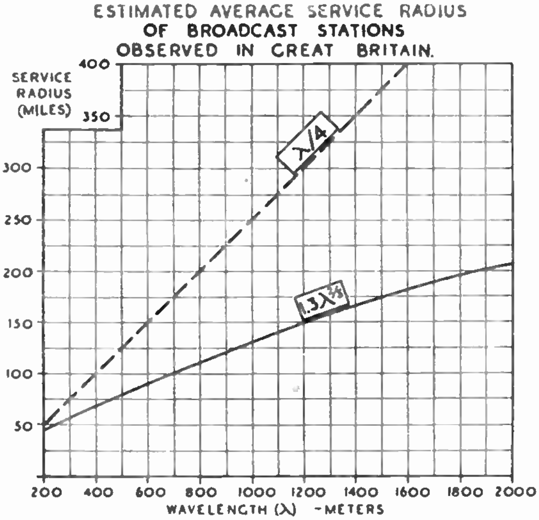

Fig. 3.

Service Area, Conclusions

It is thought that, in view of these comments, the assumption made for service range in the R.I.C. plan should be reconsidered, which, of course, will mean reconsideration of the whole plan.

The main differences of opinion appear to be due to the different standards that have been accepted at different times for satisfactory broadcast service. In my opinion, for a satisfactory standard, it is necessary for the ground field to be at least twice the space field for 95 per cent. of the time.

The R.I.C. plan is also optimistic in its assumption that the soil conductivity is as good as 10^{-13} c.m.u. at most places. There are very considerable areas where this is not so and it must be remembered that an intervening bad patch of soil can introduce considerable attenuation. If the soil conductivity is n times reduced, then the attenuation will be increased by $\sqrt{n}$.

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Shared Wavelengths

In Appendix III of the R.I.C. plan a number of shared wavelengths are shown. The table shown on Fig. 4 gives the position relating to these shared wavelengths.

It will be seen that the ratio of ground wave intensity of wanted station to space wave intensity of unwanted station at the edge of service area of wanted station varies from 7 : 1 to about 12½ : 1 (17 db. to 22 db.). It is doubtful if this is good enough, as when the wanted station only uses low modulation, the crosstalk of the unwanted station may be quite considerable. Also, if between the wanted station and the receiver there should be soil of a lower conductivity than between the unwanted station and the receiver, these ratios may be further reduced. In this connection, it might be mentioned that between 1926 and 1938, during night-time, very considerable interference was experienced at Nottingham (at a distance of 57 miles from the North Regional transmitter) from the Jerusalem transmitter working on the same frequency as the North Regional transmitter.

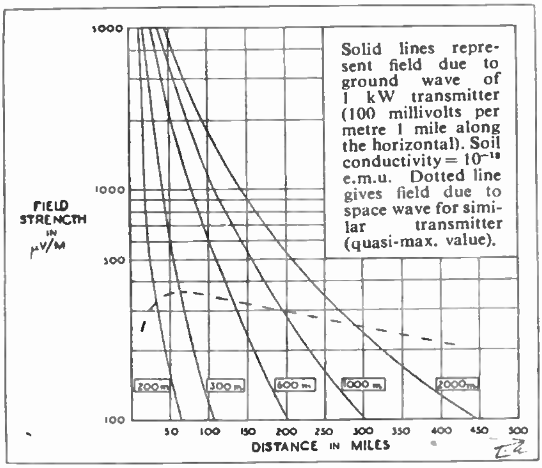

Fig. 4.

Insufficient Allowance for National Requirements

Examination of Appendix IX of the R.I.C. Report will show that many countries are not properly covered, even by their own transmitter. As examples, I mention Denmark, Portugal, Italy and Jugo-Slavia, although there are many others one could mention. In the case of the U.S.S.R. the position is even worse because while two main areas covered by long waves cover most of the Russian Soviet Republic and the Ukrainian Soviet Republic and three shorter wavelengths covering the Esthonian, Latvian and Lithuanian Soviet Republics, have been provided for, the Moldavian, Byelo-Russian and Karelo-Finnish Soviet Republics have no wavelengths allocated to them. It should also be borne in mind that the Asiatic half of the Russian Soviet Republic and a further seven Soviet Republics in Asia are so close to Europe that they cannot be completely ignored.

The authors of the plan no doubt appreciated that there is some difficulty in this connection by including "N," where "N" is an unspecified number, as Regional services for Russia in Appendix V of the R.I.C. plan. Unfortunately, the 11 forgotten Soviet Republics cannot be dealt with on a purely regional basis.

It will be seen from the foregoing and from subsequent discussion that, firstly, the frequencies allocated by the R.I.C. plan are not all available for broadcasting owing to requirements of existing other services; secondly, even if all these broadcast channels were available, the plan does not provide enough national channels adequately to cover all countries; thirdly, the service range for broadcast stations in the R.I.C. plan is far too optimistic to be acceptable to engineers; and, fourthly, the use of shared wavelengths as recommended in the R.I.C. plan would cause interferences between stations.

A European broadcasting system based on the R.I.C. plan would result in a large majority of listeners obtaining a bad service and, in spite of that trouble it would be to change over to such a system, it would not produce any noticeable improvement over present-day broadcasting.

Perhaps a less ambitious plan giving one good national programme for each country instead of two that would be given according to the R.I.C. plan, would be preferable and might be practicable.

Col. J. Parker : Taking the long-wave band into which R.I.C. planned to extend, it will have to be realised that this extension will seriously interfere with important existing services.

If the band is extended, it will be necessary to find ether space for the displaced services, and any replacement bands will have to satisfy the difficult technical requirements involved, and will have to be such that the extremely large capital value which is represented by these services is not entirely scrapped. Some idea of the magnitude of the problem involved may be gained from the following data :—

(1) In the long-wave band proposed by the R.I.C. there are some 360 allocations, each with at least one station ; many are channels used on a common basis, for example, by ships or aircraft. Although power registrations are only made for some 50 per cent. of these channels, the aggregate power is of the order of 250 kW.

(2) 13 allocations for marine communications.

(3) 32 aeronautical communication allocations.

(4) 30 meteorological allocations.

(5) 40 aeronautical or marine navigational allocations used, for example, for beacons.

(6) 5 aeronautical or marine D/F allocations.

(7) 4 main aircraft safety allocations.

The following special cases indicate some of the worst aspects of this problem :

290-320 kc/s	Beacons used by Germany, Denmark Great Britain, Sweden. Estonia Finland and Norway.
342 kc/s (877 m.)	Aero D/F in Europe
345 kc/s (870 m.)	„ „ „
338 kc/s (754 m.)	„ „ „
373-382 kc/s	Marine local beacons
375 kc/s (800 m.)	Marine D/F.
380 kc/s (789 m.)	R.A.F. Safety wave.
385 kc/s (779 m.)	„ „ „
389 kc/s (771 m.)	„ „ „
393 kc/s (763 m.)	„ „ „
400 kc/s (750 m.)	Aircraft beacons.

These figures are based on the Berne list, since it is not felt possible to consider the special arrangements which have been made by the United Nations since the outbreak of hostilities in Europe. However it is of interest to note in this connection that the Allied Nations' policy has, in general, been to make no Berne registrations during the war, so that the picture given errs, if anything, on the side of presenting a too optimistic view, since many of the war-time services which have not been registered with Berne will have to continue in future.

M. Exwood : I am surprised that in the question of the permissible ratio of direct to indirect ray, the effect of the modulation index has not been considered.

It is well known that the shape of the distorted spectrum due to interaction of the direct and indirect ray is dependent on the ratio of paths difference of the direct and indirect ray and the wavelength.

A rough calculation shows that for a transmission at 1 Mc/s and considering a single reflection in the E layer, the effect at a receiver 75 miles from the transmitter is that when the carrier frequencies of direct and indirect ray arrive out of phase, the side bands frequency corresponding with 500 cycles will arrive in phase. This means that at the moment the transmitter is 90 per cent. modulated, the permissible strength of the indirect ray is only about 1/20th of the strength of the direct ray, if over-modulation and severe distortion are to be avoided.

The map given for regional coverage in Appendix 8 is somewhat misleading, in that the radii of the circles do not correspond with the distance in miles equivalent to ¼ wave length in metres. There are, furthermore, large stretches of Great Britain which are not covered by the transmitters. I particularly note the areas of Hull, Cumberland (where reception conditions are extremely difficult) and North Wales.

I observe that in the regional wave bands 11 wavelengths have been allocated to Great Britain alone. I question whether the ratio of 11 to the total number of channels available is in proportion to the ratios of population in England to the population of the whole of Europe or in the ratio of the area of Great Britain to the area of Europe.

It appears to me that Great Britain would be favoured at the expense of other nations.

I also note that in the calculations for service area only, the question of fading has been considered, and not the question of Luxembourg "effect." I consider that there will be many areas where the limitation of reception will not be due to selective fading, but due to this effect, particularly when many high powered long wave stations are added to those at present operating.

Mr. M. G. Scroggie : I should like to support Mr. Exwood in his criticism of the distribution of service areas shown in the R.I.C. Plan. It is certain that if the Plan were to come before an international conference, where the majority would not be biased in favour of Great Britain, the proposed allocation of frequencies would be unacceptable.

Accepting the ranges shown in Appendix IX, it will be seen that whereas the lowest frequency transmitters for some countries, such as Denmark and Jugoslavia, leave large parts of those countries uncovered, the frequencies allocated to Great Britain are shown as having service areas of which at least 60 per cent. extend beyond the coasts. In the matter of regional transmitters, too, this country seems to be disproportionately well provided ; and looking at Appendix VIII it appears that such transmitters are being wastefully used, notably along the east coast, where about 50 per cent. of the service areas is over the sea, while such important districts as Hull are left out. This would not have been quite so bad if B.B.C. sites, e.g., Burghead and Stagshaw, had been assumed. It is surprising, in this connection, that the Plan makes no mention of directional aerials, which were a feature of the Montreux Plan and were in successful operation before the war. Nor is any reference made to the so-called anti-fading aerials, which might be expected to influence the range/ratio at the higher frequencies.

The R.I.C. Plan proposes a channel separation of 11 kc/s. Seeing that a change is contemplated, why not 10 kc/s? I am very heartily in sympathy with the desire to increase the spacing, but 11 kc/s is a compromise that gets the worst of both sides of the argument. The difference in quality and freedom from interference between 10 kc/s and 11 kc/s is not likely to be very appreciable to listeners, whereas by rejecting the opportunity to use a 10 kc/s spacing the interference from American stations, already a nuisance, is likely to be serious when the 1,000 and 2,000 kW stations envisaged by Mr. Clark become common. It is remarkable, too, that the Industry should not appreciate the very great advantages of a 10 kc/s spacing in making possible a simple and rational system of dial marking by giving each channel a number consisting of its frequency divided by 10. Such integral numbers would obviate the present cumbersome way in which channels have to be announced to the public in wavelengths and frequencies, and at the same time would be equally useful for technical purposes. Again, the 10 per cent. increase in channels corresponding to substituting 10 kc/s for 11 kc/s would yield a reserve which, according to the evidence put forward in this discussion, may well be needed. The 11 kc/s spacing is quite inadequate for really high quality; it will be necessary to rely on bands in the V.H.F. region for that. So I advocate an increase to 10 kc/s only, which would give really substantial benefits in addition to a proportion of those aimed at by the 11 kc/s exponents.

Mr. D. St. John Jones : The Plan will be generally welcomed as being the first of its kind to be drawn up from first principles, but being theoretical only the authors must anticipate some modifications in its layout, mainly for political considerations. It is noted that the span of frequencies required for the Plan is the largest yet, 150-295, 340-435 and 550-1,650 kc/s. Mr. Clark has taken for comparison the Montreux Plan; I do not think that the Montreux Plan will ever be implemented now; I have considered the R.I.C. Plan along with the Lucerne Plan. At the conclusion of hostilities in Europe, it appeared that broadcasting authorities were endeavouring to revert to the provisions of the Lucerne Plan, which is the last broadcasting arrangement to have been put into operation and does provide a working compromise until a new European meeting can assemble. This plan provided for broadcasting bands of 160-285 and 550-1.500 kc/s and broadcasting by derogation was permitted in the bands of 246-265, 415-460 and 515-550 kc/s. These bands are shared with other services and must be so geographically sited that they cause as little interference as possible with the other services, mainly maritime services; the broadcasting stations can be seldom reached with average receivers which are mainly used in Central European areas for broadcast relay systems. It is reasonable to assume that services operating adjacent to the broadcast bands will resist expansion into their allocations and also these services will probably be demanding expansion of their own frequency bands, thus leading to a possible curtailment of the R.I.C. Plan. It is felt that, under these conditions, a station separation of 10 kc/s would be more practicable, and, as other speakers have noted, extra advantages may be gained, especially if the European stations were laid out on the American plan, leading to a metric layout for tuning dials and to a reduction of interference from stations outside of the European zone.

I have frequently observed a 3,000 kc/s whistle on the B.B.C. Home Service channel of 887 kc/s caused by WABC New York. With regard to the principles of the R.I.C. Plan, in my opinion a most important point arises. Principles 1 and 2 have been, of course, the guiding principles of the previous plans drawn up by the U.I.R. Under Principle 3 it is reasonable to assume that broadcasting authorities will take steps to ensure that their frequencies providing for extra-territorial reception will carry programmes acceptable and, indeed, attractive to foreign listeners. Thus, the R.I.C. Plan provides for each country a European Service, a feature which is quite new in broadcasting plans and most desirable. The present system of European services has been developed entirely as a result of the pressure of propaganda during the War and have, in general, been run at the expense of domestic channels, except in the case of Germany who, when the New Order was imposed on the European ether in 1941, was able to allow the Reichsrundfunk to deploy suitable transmitters in the Occupied Countries. The provision of a European Service for each country is considered to be one of the most attractive features of the R.I.C. Plan. Nevertheless, it is possible that certain countries may not wish to avail themselves of the facilities offered by the Plan and this may lead to channel-jumping by other countries who may feel, rightly or wrongly, that they may not have had the very best deal.

An example is given by the Spanish authorities who, in 1944, purchased a 100 kW transmitter from the Telefunken concern and operated the station from just outside of Madrid on 1,022 kc/s, although Spain has always been allocated a long-wave frequency, which should be ideal for that country. Perhaps receivers with a long-wave band are not so common as they used to be. During the War there was a general all round increase in antennæ power, and 100 kW transmitters are now quite common, although some have been destroyed during the fighting. Many of these transmitters may have to run on reduced power to conform with the requirements of a new plan.

It is noted that the R.I.C. Plan makes no mention of change of power for daytime and night-time transmission nor of atennæ directivity, although the latter, by suitable distortion of the polar diagram, will be able to fill up the odd corners of countries not fully covered under normal conditions. At the present time certain transmitters, which had been altered by the Germans to operate on more advantageous frequencies, appear to have decided to remain where they are ; others have been modified to fill channels left vacant by stations which have been destroyed and there is a good deal of chaos in both the long and medium wave broadcast bands to-day. No matter what plan is settled in the future, radical changes will have to be carried out. There is sure to be a migration of regional services to the ultra high frequencies which may ease the congestion to some extent.

F. J. G. van den Bosch : Before the war we acquired quite some experience in sound broadcast on Television waves. Would it not be better to broadcast the Regional progammes on these short waves, say from 30 to 60 Mc/s, and leave the medium waveband for the National programme? This would avoid unnecessary overcrowding of the medium waveband and allow for a wider bandwidth than the proposed one, resulting in higher quality. Since it is intended to cover the whole country with a Television service, there would really be no difficulty.

F/Lt. C. B. Bovill: I wish to congratulate those responsible for the R.I.C. Plan on their scientific approach to the difficult problems of providing an efficient broadcasting service, but view with apprehension their proposal to deprive the aeronautical and navigational service bands of about 40 kc/s of their present small allocation of channels. I feel that this proposal will meet with strong opposition in aviation circles unless some form of substitute is offered for the lost radio facilities.

There appears to me to be a method of doing this which is to arrange for groups of the long wave broadcast transmitters to form the basis of a navigational aid chain operating on the principle of comparison of phases for the determination of position, used in conjunction with specially prepared maps.

With the best known of phase comparison navigational aid systems one of the basic requirements is for groups of three stations to have a harmonic relationship to one another; this should be a simple matter to arrange with the proposed 11 kc/s separation.

The adoption of the principle of making broadcast stations serve the dual role of their primary function and navigational aid would show a considerable saving in the cost of plant and in salaries of maintenance personnel.

I understand that there are no real technical or practical reasons which would prevent such a scheme being applied and think that it would solve one of the major problems of aeronautical navigation.

Mr. J. A. Sargrove: Regarding the advisability of relaying a programme by many stations all radiating in phase on the same carrier frequency, I recollect reading about a German plan in 1939 which envisaged a Continental network of such R.F. booster stations arranged geographically as the squares of a chessboard. The authors of this plan, after pointing out the advantages of this scheme in providing a fading free high field strength over a Continental area, had to admit that the plan had serious disadvantages by virtue of the fact that in certain areas in between the equally spaced "in-phase" transmitters there would be absolute cancellation of the carrier, and, therefore, no reception.

It would appear that by such means a good service could only be achieved by duplicating the entire network of transmitters on a different carrier-frequency to ensure a satisfactory field strength in all areas on at least one frequency.

I would submit the following constructive suggestion: that instead of making receivers in the future with a long and medium wave range, the latter giving at most 4-5 extra stations to any one listener possessing a good receiver, all national transmitters be operated on one wave band with A.M. and receivers be fitted with a switch to change over to F.M. for all regional programmes. F.M. broadcasting, due to the so-called "capture effect," is ideal for interference-free Regional working and it is technically possible to provide each region with ten programmes on different bands.

I would also like to draw attention to many technical solutions recently reached for F.M. reception to the problem of adopting existing A.M. receivers to F.M. reception. In some circuit schemes the substitution of a different type of valve for one already in use in the receiver, (but without the addition of any valves) and the addition only of a switchtable circuit portion built into an adapter enables the desired end to be accomplished. I feel these new schemes deserve careful examination before we commit ourselves to continuing with only A.M. transmission.

Mr. B. Wardman: The complete band from 200-490 kc/s will be required for air and maritime navigational aids, and this would seriously curtail the proposals set forth in the plan.

As the number of channels available in this band will be extremely limited, no matter how generous the final allocations for broadcasting may be, I wonder why the Committee suggested this particular allocation. Surely, and particularly if the $\frac{\lambda}{4}$ formula is accepted, the most efficient allocation is to use the longer range channels for covering larger and comparatively sparsely populated areas, and to use the shorter range channels (i.e. medium waveband) for high density localities. Thus, population per square mile in Europe varies from 700 per square mile in Belgium, 627 in Holland and 468 in Great Britain down to 22 in Norway and 2 in Iceland, and this would seem to be a most important factor.

Finally, the plan allows, in this country, three effective programme channels, comprised of two nationals and one regional. This may be an equitable distribution of existing channels, but does it represent listener, or rather consumer, demand? Will it be sufficient for the future? Personally, I suggest that many more programmes will be demanded by the listening public and that we should plan accordingly. For example, I can visualise a demand for educational broadcast channels, and when expansion of this type is considered a final requirement of up to ten channels per listener area is not an improbability and must result finally in utilising new and completely different frequencies from those considered in the plan.

[*The discussion and the authors' reply will be completed in the next issue of the Journal.*]

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