

# 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."*

Vol. IX (New Series) No. 3

March 1949

## TELEVISION DISTRIBUTION OVER SHORT WIRE LINES\*

by

Paul Adorian (*Member*)

### Introduction

In closely populated areas, and in particular in blocks of flats, the siting of television aerials presents many difficulties to individual householders.

It is usually possible to locate a good television aerial system at the top of a block of flats giving reasonably good reception. The remaining problem, therefore, is to distribute the signal received by this aerial to the tenants in the block of flats concerned.

The same problem applies to groups of houses sharing a communal television aerial. The advantages of the latter case may not be fully appreciated, but it has been established in practice that there is a considerable variation in signal to noise ratio at sites quite close to one another, depending on the relative position of the receiving aerial, transmitting aerial and sources of interference. Thus, while on one side of a road considerable interference may be caused by passing traffic, on the other side of the same road, by the use of a reflector on the receiving aerial, this interference can be reduced very considerably. It is obvious that it is a great advantage to bring up the quality of reception on both sides of the road to the same level.

Ultimately, one can visualize large groups of such local wire television distribution systems interconnected by a main distribution system.

\* M.S.S. Received, October, 1948.  
U.D.C. No. 621.397.24.

Part of this paper, originally read before the International Television Conference, Zurich, has already appeared in "Wireless World" of January, 1949.

The present paper is limited to the problem of local distribution, but reference is made to the use of the wire distribution system for the simultaneous distribution of radio broadcast programmes.

### Media of Television Wire Distribution

Four different kinds of network can be considered for the distribution of television signals :

- (1) Two-wire air-spaced networks.
- (2) Two-wire cable systems.
- (3) Concentric cable systems.
- (4) Wave guide systems.

The first of these networks is not considered satisfactory for television distribution by wire at video or higher frequencies owing to the radiation resistance of such a system, which makes it particularly prone to interference and at the same time acts as a radiator interfering with other communication systems. The second system, while theoretically workable, requires a large number of repeaters or isolator amplifiers on account of attenuation of the non-uniform system, and it is thought that it would be uneconomical. The third system, on account of its lower attenuation, can be operated with a smaller number of repeaters than the second system and is the medium considered in more detail below. The fourth system, while a distinct possibility, is not being considered in detail in this paper as the development of the art has not reached the stage where objective comparisons can be made on the economy of the system as against other systems.

**Choice of System**

There are several methods by which television programmes can be distributed.

The group of companies with which the author is associated is concerned with the distribution of sound broadcast programmes at audio frequencies to hundreds of thousands of homes in Great Britain and overseas and, therefore, is interested in the distribution of television. Accordingly, some 12 years ago, soon after the B.B.C. television transmissions started, experimental investigations were started on the most suitable method of distribution of television programmes.

The main methods by which such distribution can be achieved are as follows :

*Video Frequency Distribution*

The system of distribution at video frequencies, say 0.5 Mc/s, might at first sight seem the most advantageous owing to the simplicity of the receiving sets. It also has the advantage that for very short distances the various H.T. and other power supplies could also be transmitted on cables as well as the audio frequency sound programmes so that the viewer would have an extension loudspeaker for sound reproduction and a cathode ray tube display unit for picture reproduction with little additional equipment and no direct local connection to the electric mains supply.

After practical examination of this system, the conclusion was reached that the saving made in cost of receiving equipment would be counter-balanced by the cost of special cables and distribution equipment required. Further, it was thought, right from the beginning, that eventually, due to mass production, the price of television sets would come down to such a low figure that the technically simpler sets such as envisaged by this system, but made in smaller quantities, could not be made at much lower prices.

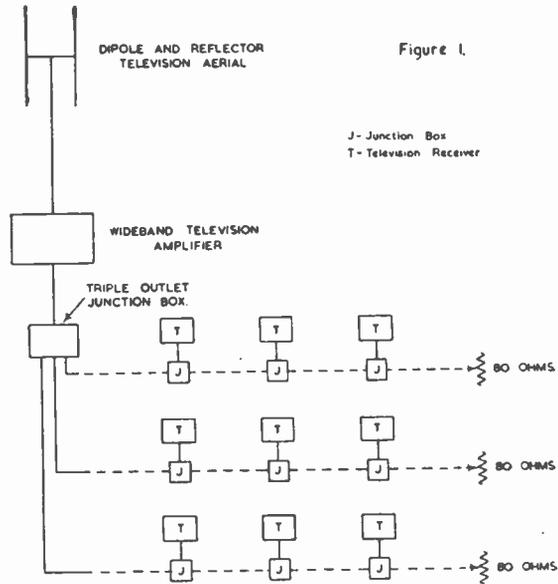
A further technical difficulty that must be taken into account in this system is that at video frequencies careful correction of lines is necessary if serious distortion is to be avoided. It must be remembered that at video frequencies the attenuation along wire lines of the low and high frequencies is very different, and such attenuation will vary considerably along the line. In addition, correction must be made for phase

distortion. Thus, such systems are very critical as regards variation in load, which would entail expensive engineering operation.

*Intermediate Frequency Distribution*

The system of distribution at an intermediate frequency carrier on which the modulation could be superimposed has also been considered. A carrier of the order of 10 Mc/s was considered with modulation of up to  $\pm 5$  Mc/s.

This system has the advantage of simplifying the television receivers by elimination of the radio frequency part of the equipment. However, it introduces more complicated equipment at the sending end and on balance could only be justified with very large systems.



*Direct Carrier Distribution*

The third system which was considered consists of receiving, amplifying and distributing over wire lines the complete carrier and sidebands of the transmitted programmes. In this case the programmes distributed are the B.B.C. London television programmes, the technical standards of which have been published elsewhere. It might be mentioned here, however, that for correct transmission of these signals, a frequency band from 41 Mc/s to 49 Mc/s should be transmitted.

The advantages of this system are numerous.

Firstly, subscribers connected to the system can utilize any television receiver suitable for the London transmission. Next, the distribution equipment is extremely simple and, what is considered most important, the system is not particularly critical as regards load variation and, once a television supply feeder is constructed and laid out to the plan described below, there is no further engineering involved except normal maintenance.

A further advantage of this system is that as the frequencies below 40 Mc/s are not used for main television distribution, the same concentric cable can be used for providing aerial inputs to broadcast receivers and possibly at a later date, when high television subscriber densities are obtained, a second television programme, if available, could be simultaneously transmitted on the system in accordance with the intermediate system referred to above.

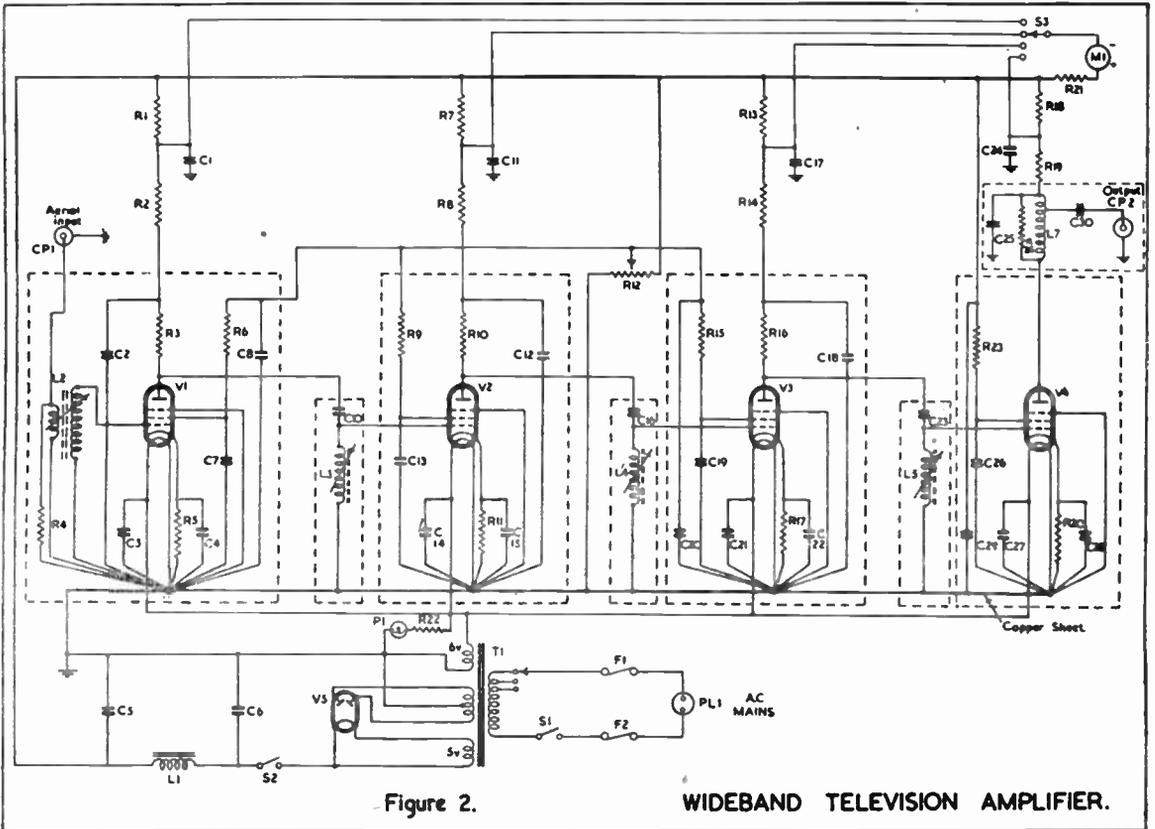


Figure 2.

WIDEBAND TELEVISION AMPLIFIER.

A disadvantage of this system may be that as a relatively high carrier frequency is used, a more expensive cable may have to be employed than for a system distributing at lower frequencies, but in practice this difference in cost is almost negligible in relation to the total cost of the installed system.

It has been found in practice that this type of distribution system can be operated with line lengths up to 500 metres.

**Description of Direct Carrier Distribution**

In view of the foregoing considerations, this system was adopted and at the time of preparing this paper 70 systems have been installed, making television service available to 9,500 households in the London area.

In view of the interest already shown, it is expected that this number will considerably increase in future and work is in hand for the installation of similar systems for several other groups.

The system used is shown schematically in Fig. 1.

A conventional vertical di-pole with reflector is used which is connected to a broad band amplifier and from this connection is made to up to three concentric cables through a matching arrangement. In the diagram the concentric distribution cables are shown in dotted lines.

It should be noted that, as explained later, the junction boxes include a loss pad which, near

and the response is about 6 db down at 41.5 Mc/s and 48.5 Mc/s, respectively.

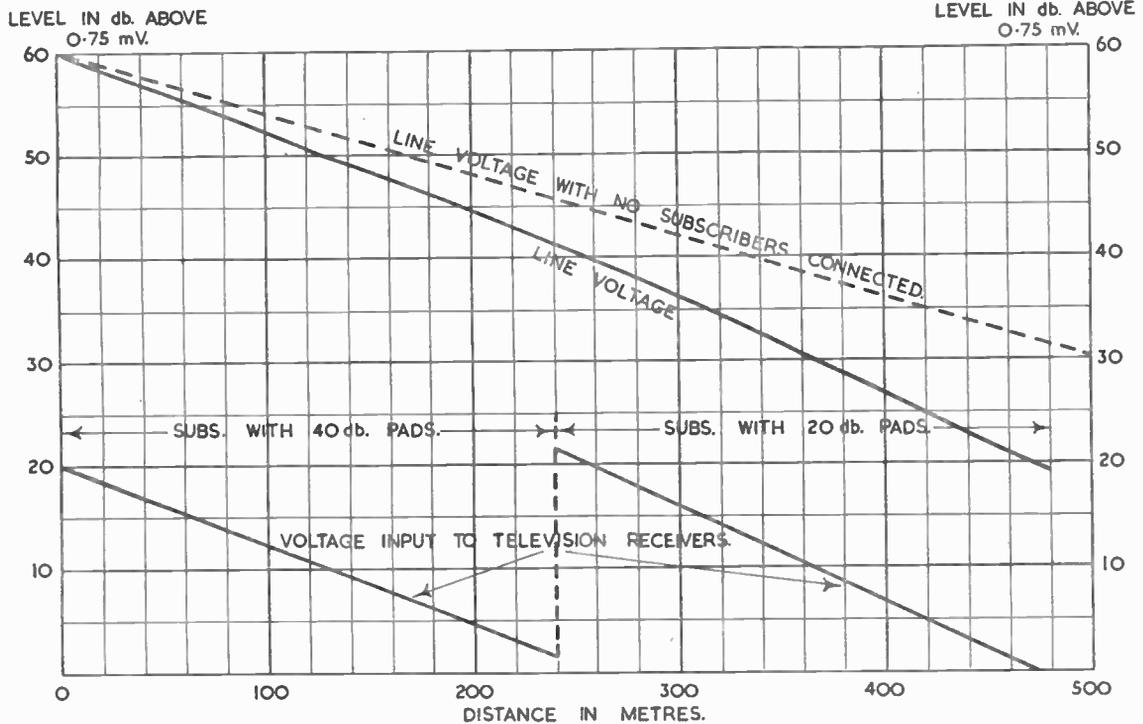
The amplifier gives an output voltage of sufficiently high level that when followed by a three-way matching pad connected to three 80-ohm lines, an input voltage of 0.75 volts is available to each line. All the four amplifying valves are of the same type and a valve rectifier is used in the built-in A.C. mains power unit.

A concentric semi-air-spaced polythene insu-

**CHARACTERISTICS OF TELEVISION  
LINE DISTRIBUTION.**

Figure 3.

(ONE SUBSCRIBER PER 15 METRES).



the sending end, introduces a 40 db loss between line and receiver, while the matching pads further away from the sending end introduce a loss of 20 db between line and receiver.

The circuit of the television amplifier is shown on Fig. 2.

This wide band amplifier gives approximately uniform gain of 55 db from 42 to 48 Mc/s. The response falls off symmetrically at each end

lated cable with the following dimensions and characteristics is used for distribution :—

Overall diameter .. ..	0.685 cm
Inner conductor diameter ..	0.091 cm
Outer conductor diameter ..	0.533 cm
Loss per metre at 45 Mc/s ..	0.06 db
Loss per metre at 1 Mc/s ..	0.009 db
Characteristic impedance of cable .. .. .	75-80 ohms.

The system has been so designed that the input voltage to receivers at different positions along the line is not less than 0.75 millivolts and not more than 7.5 millivolts.

The system is designed to supply under these conditions up to about 30 television receivers on each line spread over a length not longer than 480 metres.

Figure 3 shows the performance of such a feeder, 480 metres in length with 32 television receivers connected, distributed uniformly along the feeder.

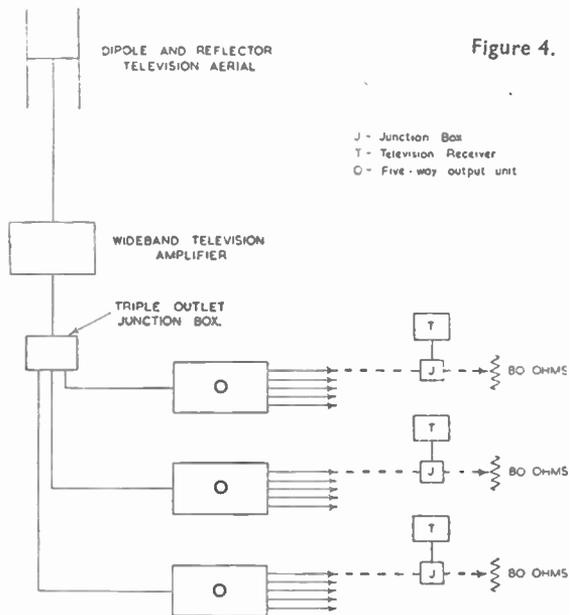


Figure 4.

J - Junction Box  
T - Television Receiver  
O - Five-way output unit

### Increasing the Scope of the System

While the system described above is able to supply over 90 television sets on three lines, a further extension of the system has been developed by means of which it is possible to feed up to 15 lines and a total of about 450 subscribers.

In this arrangement the output of the wide band television amplifier is connected to the inputs of up to three output amplifiers. Five similar one-stage amplifiers are incorporated in each output amplifier and each of these one-stage

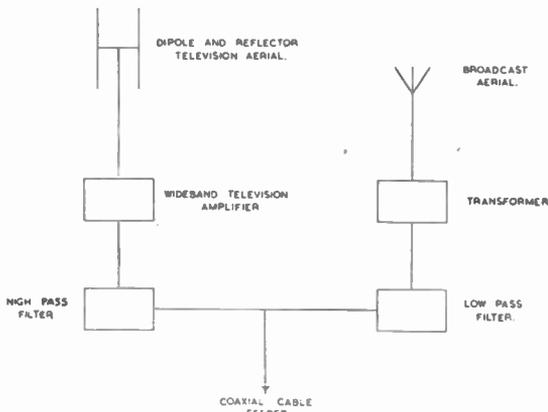


Figure 6.

amplifiers can feed one line. Thus, 15 lines can be supplied. The schematic, Fig. 4, shows the general arrangement. Figure 5 shows the circuit diagram of the output amplifier incorporating five one-stage amplifiers.

A further extension of the system is possible by extending the length of the feeders by the introduction of repeater amplifiers, but up to the time of writing this paper, this has not yet been necessary in practice.

### Television Distribution Combined with Radio Broadcast Distribution

The system has been further developed for use as a combined television and broadcast aerial system, in its present form for the distribution of medium and long wave broadcast inputs and the television distribution described above. The general sending-end arrangement used is shown on Fig. 6 and is self-explanatory.

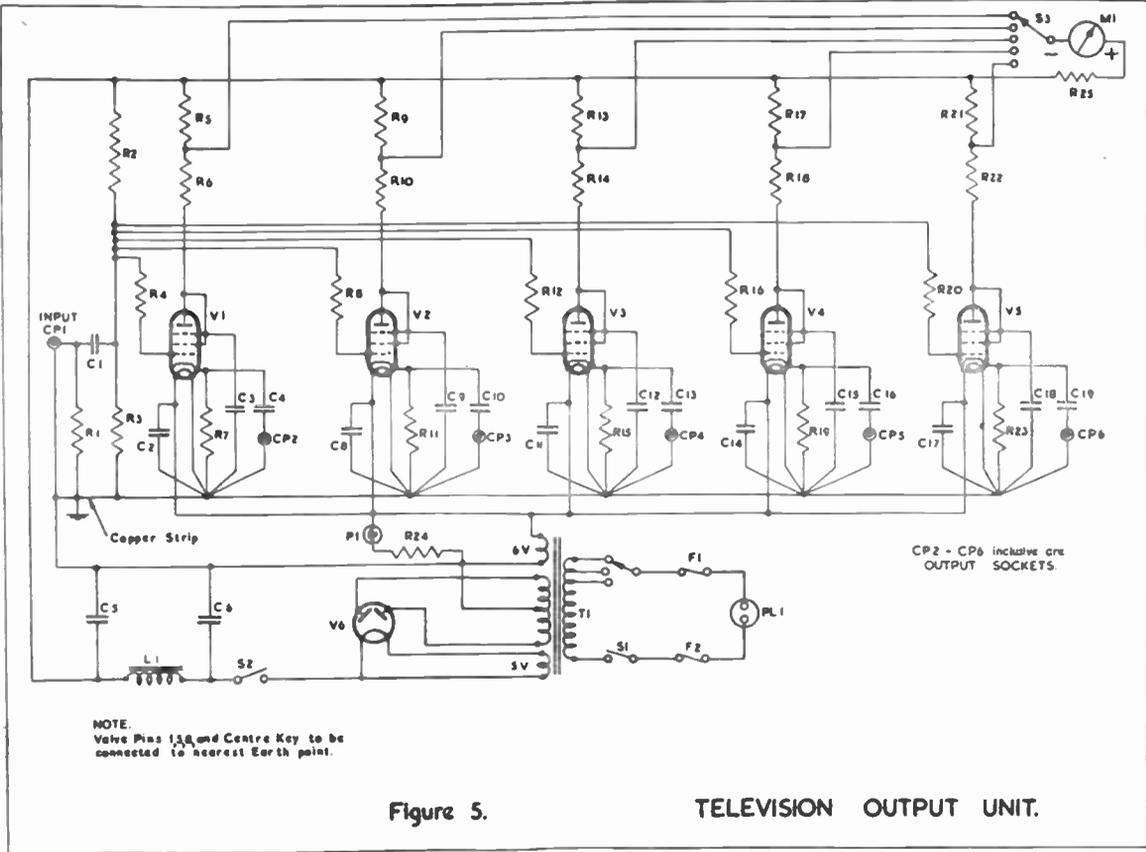
Where such arrangements are in use, it is usual to connect the aerial terminal of the sub-

The top graph in this diagram shows the attenuation along such a feeder in a completely unloaded condition but the end of the line is terminated with an 80-ohm resistance, which is always used. The middle graph shows the actual line voltage due to the attenuation caused by the connection of the television receivers, while the bottom graph shows the actual voltages as applied to the inputs of the television receivers along the line. It should be noted that the first 16 receivers are connected through 40-db pads while the second 16 receivers are connected through 20-db pads. (As the receiver input impedances are about 75-80 ohms each, in the case of 40-db pads a 7,500-ohm series resistance is used while in the case of 20-db pads a 750-ohm series resistance is used at the appropriate junction boxes.)

scriber's broadcast receiver to the concentric cable through a 750-ohm resistance and connect a small condenser which presents high impedance to the medium and long wave broadcast signals, in series with the subscriber's television set aerial terminal.

It will be noted that no wide band amplifier is shown in conjunction with the broadcast

of aerials may be difficult or impossible. The system has been developed to cater for the highest density of population that can be expected. The system can be further extended by interconnection with longer lines and direct connection to the television studios so as to deliver direct to subscribers television programmes from the studios.



aerial as this is not necessary at sites where strong broadcast signals are available but such an amplifier could be included between the aerial and the low pass filter if necessary.

**Conclusions**

A system has been developed and is in commercial operation in London giving subscribers the equivalent of a television aerial, and also combined with a medium and long wave broadcast aerial. This system is particularly suitable for closely populated areas where reception conditions may be difficult and even the siting

**Acknowledgments**

The author wishes to record with thanks permission received from Central Rediffusion Services Limited to disclose this information which is the result of development by that company. The author also wishes to thank Messrs. H. J. Barton Chapple, B.Sc., M.I.E.E., M.Brit.I.R.E., of the Engineering Division of Central Rediffusion Services Ltd., and R. I. Kinross, A.M.I.E.E., Chief Engineer of London Rediffusion Service Ltd., who have been mainly responsible for this development and who have assisted in the preparation of this paper.

## GRADUATESHIP EXAMINATION, NOVEMBER 1948.

### PASS LIST.

A total of 184 candidates entered for the whole or part of the November 1948 Graduateship Examination. This list contains all the results except those of the candidates who sat the examination at Agra and Madras, which will be published in the April Journal.

*The following candidates have passed the entire examination or, having previously passed or been exempt from part of the examination, have now passed the remaining subject(s). They are now eligible for election or transfer to Graduateship or higher grade of membership :*

ANSTEY, Harold George	London, N.16
BASSETT, Richard Anthony	Ryde, I.O.W.
BERTOYA, Hastings Charles Maxim (S)	London, E.17
BOULTER, Sidney Nelson (S)	Sheffield
BRISTER, John Arthur (S)	Leigh-on-Sea, Essex
BRULEY, John (S)	London, N.7
CARR, David Livingstone	London, N.W.5
CHESTER, Alan Sydney (S)	Blackpool, Lancs.
COLLINSON, John Dunn (S)	Brighton
FERREIRA, Tobie Muller (S)	Port Elizabeth, S.A.
GRIMM, Frank	Aberdare, Glam
HANNEY, Norman Preece (S)	London, W.C.1
HOLMES, Peter William (S)	Seven Kings, Essex
HOLSHAUSEN, Desmond James (S)	Kingwilliams- town, S.A.
JONES, Granville Paul	Blackpool, Lancs
KARPLUS, Heinz Berthold	Sidcup, Kent
LEE, Charles Tet Hien (S)	Singapore
LOCKLEY, Noel Arthur	Bridgnorth, Shropshire
MASON, Denis Connell (S)	Wolverhampton
MORLEY, Neville	King's Lynn
O'HAGAN, Michael (S)	London, N.W.9
PARANJAPE, Madhaw Krishna	Poona, India
PAYNTER, Douglas Arnold	Caterham, Surrey
PHIPPS, Stewart Alexander (S)	Liverpool
PROCTER, Antony Charles (S)	Gawcott, Bucks
RAO, Masoor Rama	Bombay, India
RAO, P. Laxminarayan (S)	Bombay, India

RICHARDSON, Leslie (S)	Norwich
ROBINSON, Victor	Fleetwood, Lancs
ROSE, Frank Edwin (S)	Droitwich, Worcs
SANGAMESWAR, Venkitachal (S)	Bombay, India
SCHILD, Rolf (S)	London, N.W.2
TILLYARD, Reginald	Dartmouth, Devon
TOMALIN, Norman Harry (S)	Rugby
TREW, Arthur Sidney	London, N.W.1
VIALLS, Arthur Frank Gostelow	Exeter
WHITEHEAD, Geoffrey (S)	Blackpool, Lancs

*The following candidate passed Parts I, II, III only :*  
FRANKS, Percy Ronald Luton, Beds.

*The following candidates passed Parts I, II only :*

BEECROFT, William (S)	Bradford, Yorks
BELL, John Ramsey (S)	London, W.4
ELDRIDGE, Dennis Arthur George (S)	Enfield, Middx
EMERY, Trevor Munslow	Nairobi, Kenya
HANDS, Raymond Kenneth	Chatham, Kent
HUMPHREYS, David John (S)	Ilford, Essex
KORCZYNSKI, Wladyslaw (S)	London, W.9
LEAN, James Leslie (S)	Townsville, Australia
LOH, Kwong Khoon (S)	Penang, Malaya
PADMANABHAN, Rajagopalachari	Trichinopoly, India
PANTON, Victor Alphonso (S)	London, W.1
QUIRK, William James (S)	London, W.4
SPRAGG, Cyril Raymon (S)	London, N.16
WARD, Simon Myles (S)	Edinburgh
WHITEMAN, Francis Clifford (S)	London, S.E.24
WILLIAMS, William Elwyn (S)	London, N.13
WOOD, Donald Trevor	Swindon, Wilts

*(continued overleaf)*

*The following candidates passed Part I only:*

ALLEN, Reginald (S) London, W.14  
 BARBER, Geoffrey Maxwell (S) Parkstone,  
 Dorset  
 BARKER Robert Williamson Scone,  
 Perthshire  
 CLAASSENS, Hennig Fouche (S) Krugersdorp,  
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 DYER, Martin Richard London, N.W.3  
 GILSON, Thomas John (S) Offaly, Eire  
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 LLOYD, Reginald Francis Melbourne,  
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 SCHOFIELD, Edward Brien (S) Manchester  
 SEARS, John (S) London, N.6  
 VADGAMA, Gulab Maganlal (S) London, E.C.2

*The following candidates passed Part II only :*

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 Cheshire  
 DANIEL, Henry George (S) Surbiton, Surrey  
 DELACOURIDES, John London, W.9  
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 FLANNERY, Thomas James (S) Hamble, Hants  
 GIFKINS, Geoffrey Charles (S) Hertford  
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 LEACH, Stanley Charles (S) London, N.13  
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 Vivares (S)  
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 VARNAKULASINGHE, Joseph Ceylon

WILLIAMS, Robert Richard (S) Bangor,  
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 BARKER, John Kenneth Cheltenham  
 BATES, James William (S) Coalville, Leics  
 BROVIG, Aanen (S) Hamble, Hants  
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 CRETCHLEY, Ronald Richard Swindon, Wilts  
 EVE, Godfrey Arnold (S) London, N.8  
 FARRAR, George Henry (S) Bradford  
 FELLOWS, Horace (S) Wolverhampton  
 FLAVELL, John Aubrey Ipswich  
 MOURAD, Abraham (S) Cairo  
 PENDHARKAR, Neelkanth Poona, India  
 Gopal  
 SPINKS, Harry Roy (S) London, N.8  
 WHITESIDE, Thomas (S) Glasgow  
 ZEIHNER, Graham Sheffield

*The following candidates passed parts I, II, IV only :*

JUSTICE, James William  
 Henry (S) London, N.5  
 LANGBERG, Edwin Aberdare, Glam  
 STANLEY, Anthony Russell (S) London, N.W.2

*The following candidate passed Parts I and III only :*

CURRAN, Arthur Joseph Dublin

*The following candidate passed Parts II and III only :*

WRIGHT, Kenneth James (S) Shepperton,  
 Middx.

*The following candidates passed Parts II and IV only :*

DIRCKZE, Andrew William (S) Ceylon  
 SOOD, Jagdish Chandra Allahabad, India

# SOME POSSIBILITIES OF HEATING BY CENTIMETRIC POWER\*

by

' R. Keitley, B.Sc.†

*A paper read before the South Midlands Section on December 16th, 1948, and before the Scottish Section on February 19th, 1949.*

## SUMMARY

A study of the basic principles, range of applications, and methods of utilization of dielectric loss heating by electro-magnetic energy at radio-frequencies above 500 Mc/s.

New problems arise because linear dimensions of the system and load are now large compared with the operating wavelength. In particular, the mode of formation of stationary wave patterns in the load, methods of preventing consequent non-uniform heating, and methods of avoiding or automatically correcting mismatch due to reflected waves reaching the generator are dealt with in detail.

Methods of localizing the dissipation of high frequency power in the load are analysed and three basic systems—resonator, beam and transmission line—are distinguished, and are illustrated by application to the performance of suitable heating operations.

### 1. Symbols

- $\epsilon$  = Dielectric Constant.
- $\sigma$  = Dielectric Power Factor.
- D = Dielectric Displacement.
- E = Electric Stress (volts per unit length).
- V = Voltage.
- P = Power.
- $\rho$  = Density.
- b = Breadth.
- d = Thickness.
- l = Length.
- S = Volume.
- c = Specific Heat.
- K = Thermal Conductivity.
- $k = \frac{K}{\rho c}$  = Diffusivity.
- $\theta$  = Temperature.
- Q = Heat flow per unit time.
- $\zeta$  = Ratio of glue to wood temperature.
- N = A number.
- U = Velocity.
- t = Time.
- T = Periodic Time.
- f = Frequency.
- $\omega = 2\pi f$  = Angular Frequency.
- $\lambda$  = Wavelength.

### 2. Introduction

The capital cost per kilowatt output for the lower frequency dielectric heating is known to be greater than for other methods of heating. For the centimetric range costs may be expected to be of the same order.

Against the advantages of any dielectric heating equipment, therefore, has to be set a greater financial risk and a greater depreciation allowance, because of a greater capital cost and possible early obsolescence.

The characteristic advantage of dielectric heating at any frequency is its ability to produce rapid uniform heating throughout the bulk of a material. In suitable applications great financial savings arise from the consequent reduced processing time and superior quality of product.

The higher frequencies for dielectric heating are most frequently required in order to obtain increased power dissipation, to produce a desired rate of heating which cannot be attained at the lower operating frequencies because the voltage gradient required would exceed the maximum safe value for the material.

The ability to localise dissipation of power is valuable where only a portion of a load requires to be heated, because it reduces the total heat

\* Manuscript Received December 1948. U.D.C. 621.365.92.029.64.

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energy which has to be supplied over the heating cycle, and may be essential where adjacent portions of the load which do not require to be heated would be damaged if subjected to the same heating.

Where, owing to inaccessibility, a load must be heated by a beam of free radiation, the minimum attainable diameter of beam at the focus is about half a wavelength, and increased frequency (reduced operating wavelength) may be required where the area which it is required to heat is small. Also, since the depth of penetration in a material is generally nearly proportional to operating wavelength, the higher frequencies may be needed to reduce the depth of the surface layer heated.

Heating operations may exist, also, which can be performed by either low or high frequency methods, for which the higher frequency equipment may be more compact, convenient, cheap or efficient.

The same techniques are basically applicable for dielectric loss heating at all frequencies or wavelengths, if all dimensions are scaled in proportion to the operating wavelength. However, the dimensions of the load to be heated are not usually varied in this way, and at high frequencies become large instead of small compared with the operating wavelength.

Thus, the larger size relative to the operating wavelength of the gaps, slits, or openings for the insertion of loads, feeder spacings, etc., would allow the loss of too much power, if not individually screened, at centimetric frequencies, so that the totally enclosed resonator, waveguide and coaxial systems, which at lower frequencies are too bulky, replace the lumped inductance, condenser, and parallel wire transmission lines of lower frequency practice.

Since, also, the fraction of power dissipated in passing through a length of load which is a constant fraction of the operating wavelength tends to be constant, multiple or continuous feed points may be necessary to ensure sufficiently uniform heating and may be balanced so as to make matching independent of load variations.

These factors are responsible for the differing relative importance of utilization techniques in the low and high frequency ranges.

### 3. Generation of Heat

#### (3.1.) General

Heat energy may be briefly defined as the energy of vibration or motion of the molecules of a substance. These vibrating molecules, mainly over a range of frequencies called the infra-red, radiate energy in the form of electro-magnetic waves which will directly excite heat vibrations in the molecules of any substance on which they impinge.

In general, a proportion of any kind of energy absorbed by a substance is converted into heat energy, whether this energy be mechanical, such as impact, sonic or supersonic elastic vibrations, electric, such as dielectric polarization or conduction current, inter-atomic, such as chemical change, or sub-atomic, such as change of energy state or structure of atoms.

#### (3.2.) Electro-magnetic Wave Energy Conversion.

The ranges of frequencies of electric and magnetic fields most used for the generation of heat in materials are shown in Fig. 1 with approximate sub-division according to the mode of utilization found most suitable over each range.

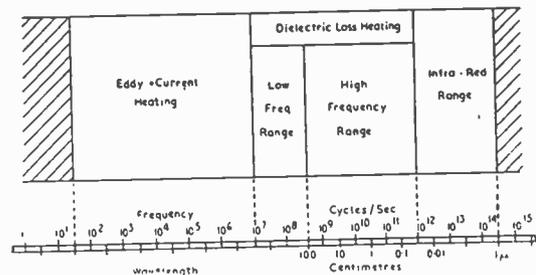


Fig. 1.—“ Heating Range ” of Electro-Magnetic Waves.

The infra-red range at the lower end is considered to merge into the range of radio waves at about 0.04 cm, in the neighbourhood of which wavelength methods of generation and detection appropriate to both ranges have been used. In general the short wavelengths and high frequencies make optical methods the only possible means of handling infra-red waves.

It is of interest to note that for wavelengths in the infra-red range (i.e. less than 0.04 cm) any stationary wave pattern formed would be too

fine to cause significant non-uniform heating, as any non-uniform temperature distribution initially produced would be substantially equalised in a negligibly short time by heat diffusion\*. Also the radiations from the hot body generators are incoherent (of no fixed relative phase relationship) and therefore, in general, there are no coherent beams capable of forming a stationary interference pattern.

Hot body generators become impracticable as the wavelength is increased into the radio range, because as the body temperature is reduced to increase the wavelength of maximum emission the total energy radiated also decreases.

At wavelengths longer than 0.04 cm in the radio range heat may be generated in materials indirectly as a loss associated with the alternating electric polarization of dielectric materials—at high enough frequencies the loss component will be mainly due to a lag or hysteresis effect in the dielectric polarization, giving an approximately constant loss per cycle, but at low enough frequencies frequency-independent leakage or conduction currents will predominate.

Polarization in a homogeneous material may be considered to arise in three ways :

- (a) By the deformation of electron distributions—called electron polarization.
- (b) By the displacement of charged atoms from their normal relative positions—called atom polarization.
- (c) By the change in average orientation of permanently dipolar molecules—called dipole orientation phenomena.

The limit to the rate of dissipation of energy as heat at any frequency within this range is set by the maximum electric stress which the dielectric will sustain without electric breakdown.

Since the maximum power which may be dissipated in a material without dielectric breakdown normally decreases with decrease of frequency the lower limit of useful frequencies is about 10 Mc/s.

The operating wavelength in the range under consideration (60 cm to 0.04 cm), is generally small enough, relative to one or more linear dimensions of the load, for stationary wave

patterns to cause many maxima and minima of electric stress and heating throughout the volume of the load, without giving a fine enough pattern for the resultant non-uniform temperature distribution to be substantially equalised by heat diffusion in a negligibly short time.

Molecular resonance phenomena may occur at the high frequency end of this range, causing large increases in the dielectric constant and losses at and in the neighbourhood of the resonance frequencies. These phenomena might be used in the selective heating of mixed materials.

Frequencies below 10 Mc/s are almost entirely used for heating by means of conduction currents induced by alternating magnetic fields. Frequencies above 10 Mc/s are in general unsuitable for this method owing to the increase of induced voltage at constant power with increase of frequency. In special cases, such as the heating of thin resistance wires, even the very high frequencies of the centimetric wavelength range are permissible.

#### 4. Dielectric Loss Heating

##### (4.1) *Heating of Uniform and Non-Uniform Dielectrics*

###### (4.1.1) *Uniform Dielectrics*

The power dissipated per unit volume of a uniform dielectric situated in a uniform alternating electric field will be proportional to the product of the electric stress ( $E$  volts per unit length) and the in-phase or loss component of the displacement current per unit area ( $Ef\epsilon\sigma$ ).

Thus Heat generated is proportional to ( $E^2f\epsilon\sigma$ ). If  $E$  is in r.m.s. volts per inch and  $f$  in cycles per second—

$$\text{Heat generated} = E^2f\epsilon\sigma \times 1.41 \times 10^{-12} \text{ watts per cm}^3 \dots\dots\dots(4.1.a)$$

If  $E$  is in r.m.s. volts per cm and  $f$  in cycles per second—

$$\text{Heat generated} = E^2f\epsilon\sigma \times 0.556 \times 10^{-12} \text{ watts per cm}^3 \dots\dots\dots(4.1.b)$$

###### (4.1.2) *Non-Uniform Dielectrics*

There is a number of important cases where it is required to heat non-uniform dielectrics, such as the simultaneous heating of different foods comprising a meal, in which a substantially uniform temperature rise is required, or in the

\* See Section (6) Appendix A.

heating of joints or seams containing a glue where it is most economical to concentrate heating as much as possible in the glue.

Where dielectric losses increase with temperature, or increase with change of state produced by heating, as when frozen food thaws, the problem is particularly difficult because any initial non-uniformity of temperature distribution is exaggerated by the increased dissipation of power in the hotter parts.

Since the dielectric constants and power factors of the materials comprising a composite or non-uniform dielectric load usually vary with frequency in different ways, it is sometimes possible to find a frequency giving a significant improvement in the uniformity of temperature rise.

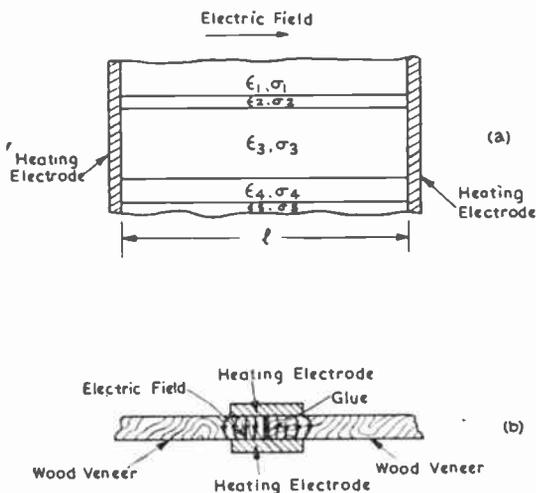


Fig. 2.—Heating of different dielectrics in parallel.

Rates of heating proportional to the heat capacity per unit volume, rather than uniform heating, are of course required to give a uniform temperature distribution.

Except where the distribution of non-uniformity throughout the volume of the load is completely random the relative rates of heating and temperature rise may be controlled by selection of the mode of application of the electric field. Some important special cases will be worked out, to illustrate this, by the methods of electrostatics, which are adequate if all significant dimensions are small compared with the operating wavelength.

*Strips Parallel to a Uniform Field.*

The general case and the important practical case of a glue line between the edges of wood veneers are illustrated in Fig. 2.

In this case the electric stress ( $E = V/l$ ) where ( $V$ ) is the voltage between the plates and ( $l$ ) the spacing between them, is the same in all the dielectrics, while the dielectric displacement ( $D = E\epsilon$ ) is proportional to the dielectric constant.

The relative rates of heating of the various dielectrics are thus proportional to the product ( $\epsilon\sigma$ ).

Since in the given practical case both ( $\epsilon$ ) and ( $\sigma$ ) are greater for the glue than for the wood, concentration of heating in the glue is obtained.

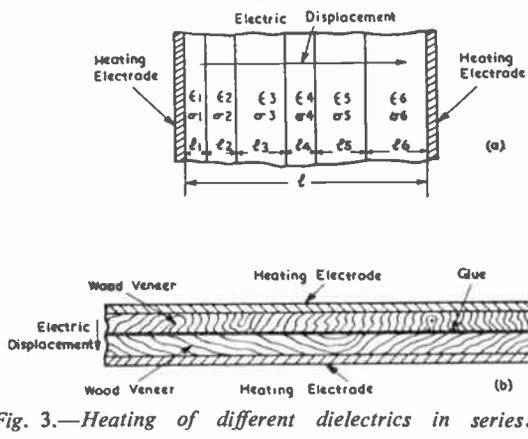


Fig. 3.—Heating of different dielectrics in series.

*Strips of Different Dielectrics arranged perpendicular to a Uniform Field.*

The general case and the important practical case of gluing two large flat pieces of wood are illustrated in Fig. 3.

In this case the dielectric displacement ( $D = E\epsilon$ ) is the same in all dielectrics, making the electric stresses in them inversely proportional to their dielectric constants ( $\epsilon$ ).

The relative rates of heating of the various dielectrics is thus proportional to the quotient ( $\frac{\sigma}{\epsilon}$ ).

In the practical case, therefore, the higher dielectric constant of the glue offsets the increased rate of heating due to its higher power factor relative to wood.

*Isolated Small Spheres of one Dielectric embedded in another.*

This case is illustrated in Fig. 4 as an approximation to random distribution of non-uniformity.

The electric field is assumed to be uniform except in the immediate neighbourhood of the spheres, which are not close enough for any sphere to be in the disturbed field due to another.

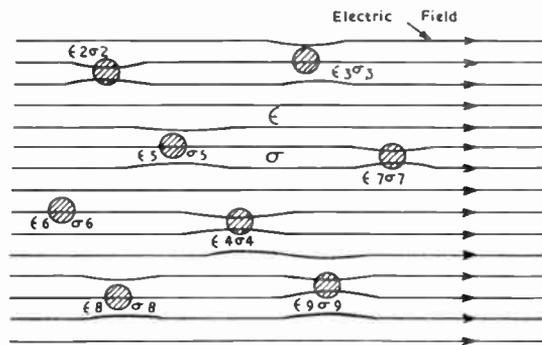


Fig. 4.—Isolated spherical particles.

Then comparing the field in the  $n^{\text{th}}$  sphere with that in the main dielectric\* (assumed undisturbed)

$$\frac{E_n}{E} = \frac{3\epsilon}{2\epsilon + \epsilon_n} \dots\dots\dots(4.1.c)$$

while the relative rates of heat dissipation are given by

$$\frac{E_n(E_n\epsilon_n)\sigma_n}{E(E\epsilon)\sigma} = \frac{9\epsilon\epsilon_n\sigma_n}{(2\epsilon + \epsilon_n)^2\sigma} \dots\dots(4.1.d)$$

The difference in the rates of heating obtained in this case is intermediate between that given for the extreme cases of layer non-uniformity perpendicular and parallel to an electric field.

*Relative movement of Field and Load, Spacing of Electrodes*

Where appreciable layer non-uniformity exists relative rotation may be expected to modify favourably the uniformity of heat generation.

Overheating of dielectric non-uniformities or projections on the surfaces of a load adjacent to an electrode may be avoided by spacing the electrodes clear of the load, thus, in effect, interposing a layer of uniform dielectric.

\* Reference (5.11) p. 79.

*(4.2) Operating Frequency and Performance Limits.*

If the operating wavelength is varied for a complete dielectric heating system, comprising a generator feeding through a transmission system with matching devices to an application head, which either contains a dielectric load or directs a beam of radiation on to a dielectric load from a distance, then the conditions of propagation throughout may be maintained unaltered by scaling all linear dimensions or distances in proportion to the operating wavelength.

The volume of a dielectric load heated under any of these conditions is thus proportional to the cube of the operating wavelength.

This assumes that the effective depth of penetration of a beam of radiation into a dielectric load, i.e. the depth before a prescribed fraction of the energy of the incident beam has been dissipated, and the actual or the minimum possible effective diameter of the beam, are proportional to the operating wavelength and that the dielectric constant and power factor of the load and any other dielectrics included in the system are maintained constant.

The maximum power available may be limited by dielectric breakdown in the load or anywhere else in the system, or by temperature rise of the generator due to dissipation of losses as heat.

The area of generator surface available for heat dissipation will, for similar generators, be proportional to the square of the operating wavelength, so that if the efficiency of the generators is constant, the maximum power which may be generated will also be proportional to the square of the operating wavelength.

If the dielectric strength (volts per unit length) of the system dielectrics is independent of frequency, the maximum total volts which may be set up when limited by dielectric breakdown anywhere in the system is proportional to the linear dimensions of operating wavelength. The impedance at any point of a system is unchanged when all linear dimensions are scaled in proportion to the operating wavelength, so that the total power flowing, stored or dissipated at any point is proportional to voltage squared or operating wavelength squared.

Under the above limiting conditions, therefore, the total power which may be put into the load is proportional to the square of the operating wavelength, while the power per unit volume is inversely proportional to the operating wavelength.

Thus for the most rapid heating of material of given dielectric constant, strength, and power factor, the highest possible operating frequency would be used.

The maximum power per unit area which may be focused on to a surface when so limited is thus independent of operating wavelength. The surface area covered by one system under these conditions is proportional to the operating wavelength, but any number of systems may, of course, be used in parallel to increase the area or volume heated.

Assuming a beam diameter slightly greater than the theoretical minimum for a 4 kW 30 cm output, the maximum attainable power per unit area would be about 5 kW/sq. ft., while for a 50 kW 100 cm output it would be 15 kW/sq. ft. The maximum attainable at infra red is below 1 kW/sq. ft.

An upper limit to the operating frequency is reached when the effective depth of penetration into the load is too small for the central portions to be adequately heated.

In consequence the maximum rate of heating which may be attained when operating at this limiting frequency is, with similarly shaped dielectric loads of different sizes, proportional to the product of dielectric constant and square of dielectric strength, i.e. to the power per unit area which may be passed through the load surface and inversely proportional to the linear dimensions of the load. Where the maximum power available from the system at a given frequency when concentrated so as to reach the limit of dielectric strength of the load covers a smaller area than that which it is desired to heat, extra systems may be used in parallel either to cover adjacent areas or each to cover the whole area to be heated.

If a wide range of frequencies is capable of performing the desired heating other factors will determine the frequency chosen. A relatively long wavelength may assure negligible non-uniformity of heating due to standing waves, or the use of a relatively short wavelength, since the spacing between maxima and minima is

small, may facilitate averaging out the non-uniformity of heating by relative movement of the pattern and load.

#### (4.3) *Reflected Waves in the Dielectric Load.*

##### (4.3.1) *Stationary Wave Patterns, their Creation and Effects*

When travelling electro-magnetic waves in the load suffer repeated reflections at the load boundaries, a stationary wave pattern is set up with adjacent maxima or minima of intensity spaced about half to one wavelength.

Where all the dimensions of the load are not small compared with this distance, there will be an appreciably non-uniform distribution of electric stress, and hence of dielectric loss heating and temperature throughout the volume of the load. Also, for a given permissible maximum value of electric stress set by dielectric breakdown, the average and the average of the squared value of the electric stress, which is proportional to the average rate of generation of heat, are reduced.

It is thus important to study the mode of formation of these patterns in order to find means of avoiding them or counteracting their effects. Stated in the most general terms, a stationary wave pattern will be formed if at least two systems of waves travelling in different directions, of the same frequency and not polarized in planes at right angles, are present in the same volume of space.

There is an infinite variety of such patterns and some simple important types will be described.

##### *One-Dimensional Pattern*

This form of pattern is so called because it is formed by waves travelling in opposite directions along a single line of motion. It most frequently occurs in transmission systems such as wave-guides, coaxial lines, parallel wire, or strip transmission lines used to heat long strips or seams of dielectric material, when energy not dissipated in the load is reflected back from the ends of the system remote from the point of excitation.

The formation of such a pattern may be illustrated by considering the sum of two waves of unit amplitude travelling in opposite directions along the line.

Resultant wave

$$= \sin 2\pi \left( \frac{t}{T} - \frac{x}{\lambda} \right) + \sin 2\pi \left( \frac{t}{T} + \frac{x}{\lambda} \right)$$

where the first term represents a wave travelling from left to right and the second a wave travelling from right to left with velocity  $U = \frac{\lambda}{T}$ . Or alternatively it may be written in the equivalent form,

$$\text{Resultant wave} = 2 \sin \left( \frac{2\pi t}{T} \right) \cos \left( \frac{2\pi x}{\lambda} \right),$$

which represents a wave which is stationary in space whose amplitude varies sinusoidally with time at any place, because of the factor  $\sin \left( \frac{2\pi t}{T} \right)$  and whose peak, mean or r.m.s. amplitude varies sinusoidally along the X-axis according to the factor  $\cos \left( \frac{2\pi x}{\lambda} \right)$ . The intensity thus has zero points spaced  $\frac{\lambda}{2}$  apart along the X-axis and maxima similarly spaced, adjacent maxima being in antiphase.

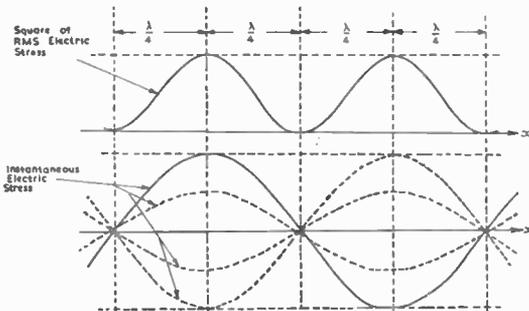


Fig. 5.—One-dimensional stationary wave pattern.

Fig. 5 shows the amplitude distribution along the X-axis at various instants of time, and also the distribution of r.m.s. amplitude squared, to which the heating effect is proportional.

### Two-Dimensional Patterns

A simple form of this type of pattern is obtained by superimposing two one-dimensional patterns in the same plane, and with the same plane of polarization, so that the lines of propagation of the component travelling waves are at right angles.

The resultant standing wave pattern shown

in Fig. 6 may be shown to be given by the expression.

Resultant wave

$$= \sin \left( \frac{2\pi x}{\sqrt{2}\lambda} \right) \sin \left( \frac{2\pi y}{\sqrt{2}\lambda} \right) \sin \frac{2\pi t}{T}.$$

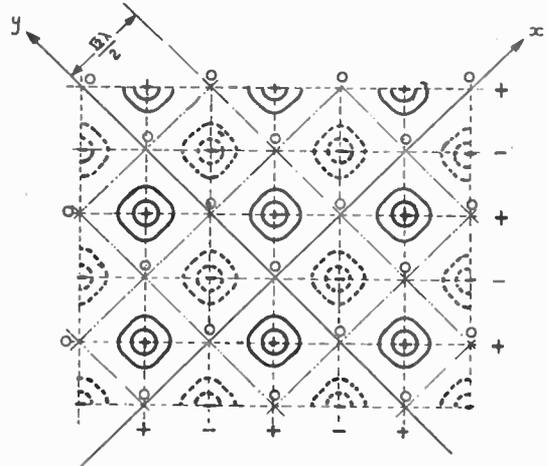


Fig. 6.—Two-dimensional stationary wave pattern.  
 - - - - - Zero lines of resultant two-dimensional pattern.  
 - - - - - Positive and negative maximum lines of component one-dimensional patterns.

The spacing between maxima or minima is greater than in the one dimensional case and equals  $\left( \frac{\sqrt{2}\lambda}{2} \right)$ . An infinite variety of such patterns may be produced by superimposing the two components at different angles in the given plane.

In practice such patterns may be set up when heating dielectric material in sheet form between flat electrodes.

### Three-Dimensional Patterns

The subject of three-dimensional patterns is developed in the extensive literature on wave-guide resonators \*

#### (4.3.2) Elimination of Non-uniformity of Electric Stress or Temperature

It is preferable to correct the non-uniformity of the electric stress distribution, thereby not only removing the cause of the non-uniformity of temperature distribution in a uniform dielectric but also obtaining the maximum possible dielectric-breakdown limited average rate of heating.

\* Reference (5.9).

If this is not possible the non-uniformity of temperature distribution may be reduced by periodically changing the stationary electric stress pattern, or causing relative movement between it and the load so that the total heat generated in any portion of the load over a sufficiently small interval of time is as far as possible equalized.

*Methods of Obtaining a Uniform Electric Stress Distribution*

*Transmission Line System*

In a transmission line system it is possible to avoid the reflections which set up the stationary wave patterns of electric stress. One way of doing this is to increase the length of the transmission line system until substantially all the power is dissipated in the load before the ends of the system are reached. Non-uniformity of electric stress due to a small residual reflection at the ends, or the continuous dissipation of power along the line, may be counteracted by variation of the volume into which the field is concentrated, or by suitably graded continuous or multiple power feed, along the length of the line.

*Loop Transmission Line System*

Another way is to form the system into a complete loop, Fig. 7 in which waves, which are excited by a suitable directional coupler, travel round the loop in one direction. Discontinuities which would cause reflected waves round the loop in the reverse direction, with consequent formation of a stationary wave pattern, must be avoided. Thus where the load does not occupy the whole of the loop, its ends, or its entry and exit from the system, should be tapered.

*The Multimode Resonator*

In a resonator system the only way of equalizing the distribution of electric stress is by the superposition of a number of different stationary wave patterns.

These patterns may be set up by the simultaneous excitation of the system by different frequencies, and also by the simultaneous excitation of different modes by the same frequency.

Any hollow conducting cavity has associated with it an infinite number of resonant frequencies, each corresponding to a different configuration of electromagnetic fields in the cavity. As one or more dimensions of a cavity resonator are increased, becoming large compared with the operating wavelength, it becomes possible to excite an increasing number of modes of oscillation or field patterns in the cavity. The intensities of excitation of the various modes are determined by the method of excitation of the resonator, the degree of internal coupling between the modes, the broadness of the resonances and the ratios between the resonant frequencies for the various modes and the exciting frequency.

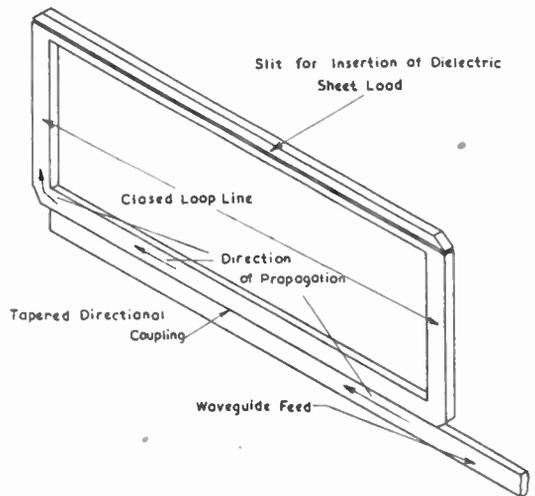


Fig. 7.—Directional tapered excitation of closed loop transmission line.

For large resonators of this type, the number of modes  $d^N$  in a range of wavelength  $d\lambda$  is

$$d^N = 8\pi \frac{S}{\lambda_1^4} d\lambda$$

where  $S$  is the volume of the resonator and  $\lambda_1$  is the centre of the wavelength band  $d\lambda$ .

The number of resonant states  $N$  in such a resonator with wavelength greater than some minimum wavelength  $\lambda_2$  is given approximately by

$$N = \frac{8\pi}{3} \cdot \frac{S}{\lambda_2^3}$$

this relation is stated to be quite accurate even for low values of  $N^*$

By control of the intensity of excitation of the various modes in large resonators of this type it should be possible to attain a substantially uniform distribution of the r.m.s. electric field intensity.

The density of spacing of resonant frequencies in the large multimode resonator is such that, with normal load losses, adjacent resonant peaks overlap to the extent that significant detuning of the resonator cannot occur. The changes of input impedance are thus reduced from the large values associated with resonator detuning to the much smaller values caused by variation of total load losses.

The conditions of operation of the matching devices of section (4.4.2) under conditions of changing load or movements of load or resonator to make the load heating more uniform, are thus easier with the large multimode resonator than with the small or minimum size resonator.

*Methods of Obtaining a Uniform Temperature Distribution*

The methods to be discussed are for suitably averaging out the non-uniform heat generation due to a stationary wave pattern of electric stress, which it is impracticable to eliminate.

The object is to attain a desired degree of quality or uniformity in the heat treatment of the dielectric load.

The effect of non-uniformity in the temperature distribution on the quality of heat treatment is dependent both on the degree of non-uniformity and on the length of time for which it persists. Both these factors are in turn dependent on the degree of instantaneous non-uniformity of heat generation, the length of time over which it is averaged out, and the rate at which it is equalized by heat diffusion.

The general method of averaging out the heat generation over a suitable period of time is to produce suitable relative motion between the stationary wave pattern and the load. The nature of this motion must be carefully selected in relation to any symmetry of the stationary wave pattern if systematic non-uniformity is not to persist.

The relative movement may be produced by movement of the load, or by causing the pattern

to move by movement of the walls of the resonator or of a small vane inside. Discontinuous motion of the pattern may be produced by exciting the resonator at given points for given fractions of the total heating cycle selected in relation to the actual stationary wave pattern to give the most uniform average heating. Motion of the pattern may also be produced by modulation or switching of the exciting frequency.

In many cases the exact location of, and spacing between, maxima or minima of a stationary wave pattern is uncertain and variable. In such cases in order to approximate closely to uniform average heating throughout the volume of a dielectric load, the load must be so moved that every point in it scans with sufficient fineness a volume whose linear dimensions in any direction are many times the minimum length over which the pattern repeats.

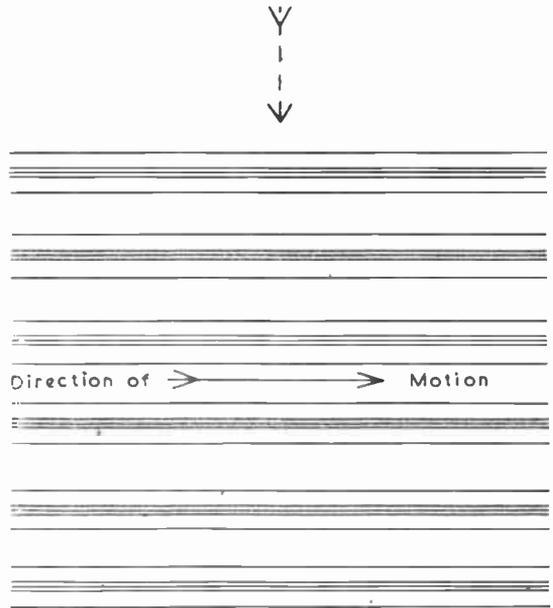


Fig. 8.—Heating distribution in dielectric load with linear motion in two-dimensional pattern.

Fig. 8 shows the effect of linear motion through the two-dimensional pattern of Fig. 6, the intensity of heating now varying in one direction only, provided the motion is at constant speed through the exact repetition length of the pattern, or is sufficiently greater than this for the variation of intensity of the

\* Reference (5.7).

residual portion, or of the intensity-time relation throughout the volume of the load to be negligible.

Fig. 9 shows the effect of rotation of the load, the heating pattern now forming concentric circles. The dotted circles show how approximate averaging may be secured by simultaneous rotation and movement of the centre of rotation.

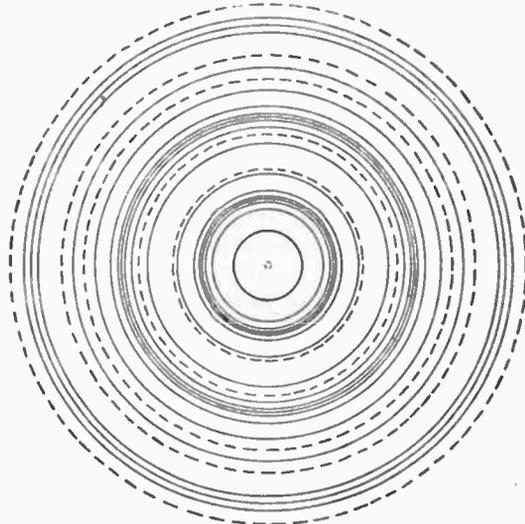


Fig. 9.—Heating distribution in dielectric load.  
Rotation in two-dimensional pattern.  
Intensity distribution when rotated about a zero.  
Maximum circles when rotated about a maximum.

The best practical scheme is probably the use of circular motions of translation thus avoiding sudden velocity changes, several different incommensurable rates of rotation being superimposed, of amplitude roughly equal to the repetition length, with or without rotation of the load.

(4.4) *Reflected Waves reaching the Generator*

When, owing to unbalanced discontinuities, a resultant reflected wave reaches the generator, several undesirable effects occur. The impedance presented to the generator will vary with the length of transmission line, repeating every half wavelength, while the greater the length of transmission line, the more rapidly will this impedance change with change of operating frequency, tending to cause instability of the generator. Increased power dissipation in the generator and the transmission line, reduced power output, and overheating of output seals

by the increased voltage stress due to the stationary wave pattern also occur.

It is preferable to eliminate reflections at their source, thus securing minimum frequency sensitivity, but where this is not possible a separate matching device to provide cancelling reflections must be inserted between the generator and the load, as close as possible to the source of reflections, in order to minimize the increase of frequency sensitivity.

(4.4.1) *Avoidance by the Tapering or Balancing of Discontinuities\**

In transmission type heating systems it is possible to avoid any net reflections due to a change of impedance presented to the wave from the generator by tapering this change over a sufficient length in terms of operating wavelength. Thus, if for every point on a suitably graded taper another point is, as far as possible, found a quarter wavelength away to provide cancelling reflections, there will be, except at certain frequencies, a fraction of a quarter wavelength whose reflections are not neutralized. The more gradual the taper the less the reflection per unit length, and the smaller will be the maximum value of the residual reflection.

Reflections due to the change of impedance created by the introduction of the dielectric load into the transmission system may be kept below any desired level by a sufficiently gradual introduction of the load into the system, or of power into the system containing the load.

The power factor and loss factor of the load determine the length of system required to dissipate substantially all the power supplied. By increasing this length to prevent significant reflections from the ends reaching the feed point, net reflections may be kept below any desired level, in spite of change or movement of the dielectric load.

Normally, with transmission systems, the load is passed continuously through them, so that the uniformity of heating is not affected by the reduced rate of heating over the tapered entry, or anywhere along the length of the system.

A tapered coupling between two waveguides is shown in Fig. 10 in which energy is fed from the generator along the lower guide and gradually transferred over a length of several half wavelengths by way of a long narrow slot

\* Provisional Patent No. 10020/47.

in a common narrow face, to the upper guide, which is split to permit insertion of a dielectric sheet load.

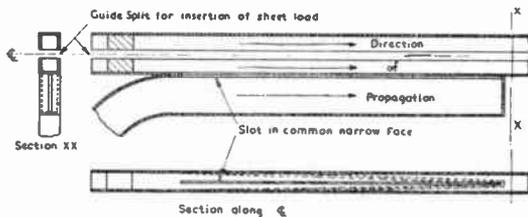


Fig. 10.—Directional tapered coupling between guides by means of long common slot.

#### (4.4.2) Cancellation by Automatically Controlled Matching Devices\*

Where it is not practicable to prevent reflected waves arising, a matching device must be inserted to provide cancelling reflections.

Mismatching, due to changing the load, moving the load, or variation of the dielectric properties of the load with change of temperature

the phase and fractional magnitude of the reflection introduced may be obtained. There is a variety of practical matching devices.† For use with the proposed system of automatic control, it is necessary that the adjustment corresponding to complete correction of the mismatch be either attained or closely approached after a small number of adjustments of each control individually to the best match. The adjustments may be the original adjustments of the matching device or any convenient functional combination of them. Methods which are satisfactory are the stub line of adjustable length (reactance) and position (phase), the combination of fixed position variable reactance stub line and variable ratio quarter wave transformer, and two quarter wave transformers spaced one-eighth wavelength apart.

A complete scheme for automatically controlled matching is shown in Fig. 11. The directional coupler is used to extract a portion of the reflected wave which it is desired to

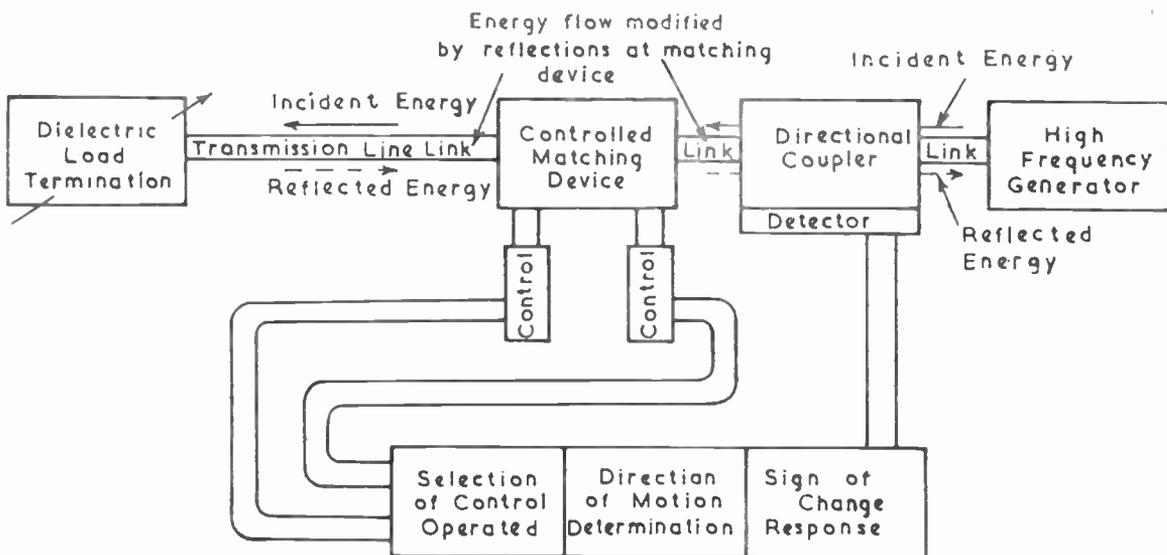


Fig. 11.—Block diagram of automatically controlled matching scheme.

over the heating cycle, occurs too frequently or too rapidly for correction by manual readjustment of the matching device to be practicable. A system of automatic control must, therefore, be devised.

A matching device must have at least two controls in order that independent variation of

eliminate and to apply it to a device such as a crystal rectifier, which provides a D.C. output whose rate of change is always of the same sign as that of the reflected wave. In order to find the setting of a control which gives a minimum value of the reflected wave it is sufficient that the direction of motion of the control be immediately

\* Provisional Patent. (B.T.H.)

† Reference (5.7).

reversed when it moves in such a direction as to increase the D.C. output. This is the function of the circuit which is responsive to the sign of the change in the D.C. output and which operates circuits determining the direction of motion of the control. When once a minimum setting on any one control has been found the system will oscillate about this setting with an amplitude depending on the sensitivity of the control. At each reversal of the direction of motion by means of the operation of some counting device such as a notching relay, the control circuit is transferred to the other control or controls of the matching device in a pre-determined order. The device may readily be rendered quiescent when the reflected wave has been brought below a predetermined level, thus eliminating unnecessary searching.

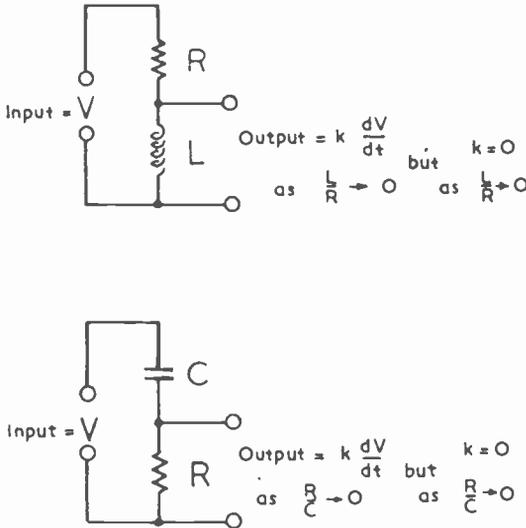
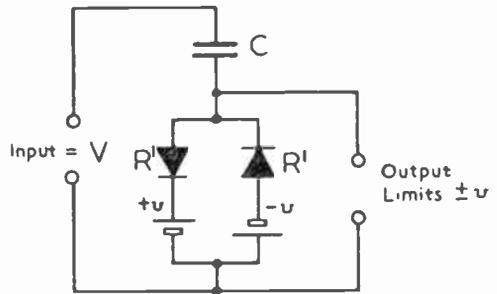


Fig. 12.—Output dependent on rate of change (typical differentiating circuits).

The simple differentiating circuits, Fig. 12, have been found unsatisfactory for indicating the sign of change of the controlled quantity, because in order that the outputs may reverse without serious time lag when the rate of change of the controlled quantity changes sign, they must always be a small fraction of the input changes. The output for a given total change is also inversely proportional to the time taken or directly proportional to the speed of operation of the control.

The circuit of Fig. 13 provides exactly what

is required. Over the range  $+v$  to  $-v$ , which need only be just greater than the minimum voltage required to operate the direction-of-motion determining circuits, the rectifiers  $R^1$  offer a very high resistance so that substantially the whole of the input voltage changes appear across the output. When the change is great enough to tend to carry the output voltage beyond these limits the rectifiers  $R^1$  become of very low resistance and prevent this. Any further increase in the same direction then appears across the condenser  $C$  by virtue of the charge which flows through the rectifiers. If the direction of change reverses, the rectifiers are immediately brought on to the high resistance portions of their characteristics, so that the full value of the change appears across the output. Since the condenser  $C$  charges very slowly through the high inverse resistance of the rectifiers, the output is independent of the



$$\frac{dV}{dt} > 0, \quad v^1 + \int_0^t \left(\frac{dV}{dt}\right) dt \approx +v, \text{ Output } +v$$

$$\frac{dV}{dt} < 0, \quad v^1 + \int_0^t \left(\frac{dV}{dt}\right) dt \approx -v, \text{ Output } -v$$

Fig. 13.—Output dependent on sign of change.

time taken over a change up to very long times. The diode is thus the most suitable rectifier for this circuit because of its infinite back resistance.

(4.5) Applications and Techniques

(4.5.1) General

A complete dielectric heating system may be divided into three main units, which will be called the "Generator," the "Transmission Link," and the "Application Head."

In addition, fixed or adjustable devices to provide impedance matching between these main units are generally required.

### *Generators*

Available valves capable of generating significant amounts of power in the centimetric range are the continuous wave klystron, the continuous wave resonant cavity magnetron, the split-anode magnetron and the resnatron.

The resnatron type of valve is the only source available in the 50 kW range. It is a beam type tetrode which can be used either as an amplifier or an oscillator at wavelengths of 10 to 100 cm, with continuous operation at an efficiency of 25 to 60 per cent.

The split anode magnetron will develop 10 kW continuously with an efficiency of 50 per cent at wavelengths of 40 to 90 cm.

Continuous wave klystrons have been made giving about 200 watts at 7 cm at rather low efficiencies.

A continuous wave resonant cavity magnetron has recently been developed especially for dielectric heating,\* giving an output of 4 kW at a wavelength of 30 cm with an efficiency of about 60 per cent. This power is about the minimum adequate for practical use.

Dielectric heating loads present much greater and more variable mismatches to the generator than occur in radar applications, and in consequence provision must be made to dissipate a considerable proportion of the generated power internally in the generator at times. For this reason, in the design of the above magnetron generous air and water cooling are provided, while the filament heating power is made very high to swamp the back heating which occurs when the magnetron is operating into a bad mismatch.

### *The Transmission Link.*

This may in general follow conventional radar practice. The poorer matching with dielectric heating loads, and the smaller risk of dielectric breakdown compared with pulse radar operation, should make some relaxation in the standards of construction permissible.

Where flexible coaxial cables are used, loss heating of the cable, not dielectric breakdown, will be the limiting factor, and the standing wave ratio in the cable must be kept as low as possible to permit maximum transmission of

power through the cable. A solid polythene cable of diameter over dielectric of 0.910 inch and inside copper conductor of 0.250 inch will carry 320 watts continuously at 3000 Mc/s and 780 watts at 1000 Mc/s. Such a cable would carry a few kilowatts for a few minutes without breakdown. If the diameter of the cable is increased to reduce losses, flexibility is of course reduced, while there is a maximum diameter which must not be exceeded if waveguide modes are to be avoided. The limiting temperature is normally reached at the surface of the inner conductor, whose diameter might therefore be increased to reduce losses. Flexibility would again be reduced while the impedance of the cable, depending on the ratio between the inner and outer diameters of the cable, would be reduced. The inner conductor might also be made hollow to permit air or water cooling or air cooling ducts might be provided in the dielectric.

At wavelengths of 10 cm and below flexible waveguide is better. The losses of such waveguide are some 10 to 20 times greater than those of similar rigid guide.

In no case would a significant fraction of the total power be lost in the flexible connection; the losses in 10 ft. of the above mentioned polythene cable would be less than 5 per cent of the power transmitted at 1000 Mc/s.

### *The Application Head*

The termination of the system where the high frequency power is concentrated into the dielectric load will be referred to as the application head. The choice of head is a matter of operational convenience, as determined by size, number, accessibility or dielectric properties of the portions of load which it is desired to heat.

Application heads may be classified under three headings—transmission systems, resonator systems and beam heating systems.

Transmission systems are waveguide, coaxial, parallel wire or strip transmission lines in which the dielectric load is heated by travelling waves. They are characterized by the propagation of guided waves through the dielectric load, which must have sufficient length in the direction of propagation for substantially all the energy of the wave to be dissipated before the end of the system is reached. These systems are thus most

\* Reference (5.6).

suitable for heating dielectric material in sheet, strip or seam forms, or dielectric loads distributed along a conveyor belt.

If a substantial proportion of the energy is reflected from the ends of a transmission system, back and forth through the load, a resonator system is formed. In general, a resonator may be defined as a conducting enclosure in which electro-magnetic waves when excited suffer multiple reflections, which for an infinite series of frequencies, the resonant frequencies of the cavity, combine in phase to form stationary wave patterns. When energy is supplied at one of the resonant frequencies, the electric and magnetic fields in the cavity build up until the rate at which energy is dissipated in the load and cavity losses equals the rate at which it is supplied. Cavity heating is thus particularly suitable for loads which are small, of low dielectric loss and of high dielectric strength.

Beam heating systems are those in which the load is heated by a beam of free radiation directed on to it by the application head, which may consist of any convenient antenna system.

(4.5.2) *Systems for Seam Heating. (Edgewise Gluing of Plywood).\**

Seam heating has to be carried out under two main conditions.

- (a) With a thin layer of a relatively high loss glue between the edges of the material to be joined, as in edgewise jointing of wood veneers, and
- (b) without such sticking material, as in seam welding of medium or low loss plastics.

These cases will be illustrated for edgewise bonding of plywood by deriving performance figures, assuming, firstly that all the heat is generated in the glue, and secondly, that all the heat is generated in the wood.

In the process of manufacture of articles using plywood veneer boards it is often required to glue two veneers edgewise. Where, as is usually the case, this joint is only required to facilitate handling prior to the gluing of the combined sheets flat on to a surface, the joint need not be continuous or of great strength.

\* Provisional Patent No. 36458/46.  
Provisional Patent No. 168/46.

The glues used would be of the thermal setting plastic type, and for this operation would be chosen for rapid polymerization at low temperatures rather than for great strength and permanence.

The thicknesses of the veneers may be expected to vary from about  $\frac{1}{32}$  in. to  $\frac{1}{8}$  in.

Surface heating methods, such as hot strip contact heating, allow the seam to be passed through the heating system at speeds up to 60 ft./min. Higher speeds would require excessive heating system lengths or excessive surface temperature of the wood, while the necessary close contact for thermal conduction necessitates frequent stoppages for strip cleaning.

Lower frequency (below 100 Mc/s) dielectric heating methods are limited by the maximum safe voltage gradient to less than this speed, and it is found necessary to employ frequencies in the centimetric range of obtain a worthwhile improvement.

Fig. 14 shows the substitution of a waveguide heating system for the hot strips in a gluing machine.

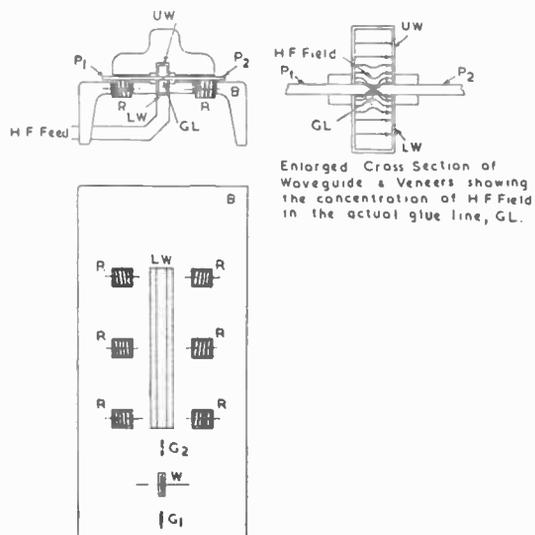


Fig. 14.—The edgewise gluing of plywood veneers by U.H.F. methods.

The plywood boards ( $P_1$ ) and ( $P_2$ ) are placed flat on table ( $B$ ). The edges to be joined are pressed close up to guides ( $G_1$ ) and ( $G_2$ ) and touching wheel ( $W$ ) and the boards are moved

forward towards powered rollers (R). Wheel (W) rotates, dipping into the glue pot, thus coating the edges of the veneers. Once under the control of the bias-grooved rollers, the edges are forced together and kept moving forward, with the glue line central in the waveguide (LW) and (UW).

In dielectric heating systems, unlike contact heating, the heat supplied per unit volume is proportional to the ratio of input power to seam speed, which must therefore be maintained accurately constant with provision for removal of power when the speed falls below a certain level, or the speed must be accurately related to input power.

*Estimates of Power Required*

Where the electric field is effectively concentrated in a breadth (*b*) of uniform dielectric material of thickness (*d*) and the length of the seam to be heated is (*l*), then total heating time (*t*) to raise this volume of material from temperature  $\theta_A$  to  $\theta_G$  centigrade is given by

$$t \propto \frac{\rho c b l d (\theta_G - \theta_A)}{P} \dots\dots\dots(4.5.a)$$

where *P* is the power supplied, or if, since the breadth (*b*) into which we may conveniently concentrate the electric field is roughly proportional to the thickness, we put  $b = 2d$ , equation (4.5.a) solving for the power (*P*), becomes

$$P = \rho c d^2 \left( \frac{l}{t} \right) (\theta_G - \theta_A) \times 8.4 \times 10^{-3} \dots\dots\dots(4.5.b)$$

in kW, cm, gm, °C and seconds.

$$\left. \begin{array}{l} \text{If } \frac{l}{t} = 60 \text{ ft./min.} \\ \text{and } (\theta_G - \theta_A) = 200 \text{ }^\circ\text{C,} \end{array} \right\} \begin{array}{l} \text{for } d = 0.25 \text{ cm.} \\ \text{P} = 25 \text{ kW.} \\ \text{and } d = 0.50 \text{ cm.} \\ \text{P} = 10 \text{ kW.} \end{array}$$

Some energy must also be supplied to make up for heat lost by conduction to unheated neighbouring portions of the material, but the calculation for heat generation in a thin glue line only shows that this loss is relatively small for heating times less than 6 seconds. With glue heating only, since the energy required to raise the temperature of the thin glue line is very small, even for quite short heating times, the energy lost by conduction to the wood is the

major proportion of the energy requirements.

With constant power supply (*P*) for a period of time (*t*) it may be shown that

$$P = \frac{l d \sqrt{K} \rho c (\theta_G - \theta_A)}{\sqrt{t}} \times 7.44 \times 10^{-3} \dots\dots\dots(4.5.c)$$

while the energy required is

$$E = P t \propto \sqrt{t} \dots\dots\dots(4.5.d)$$

Let  $(\theta_G - \theta_A)$  be increased to 300 °C, since heating will be of shorter duration and closely localised in the glue, then for  $t = 6$  secs. and  $l/t = 60$  ft./min.

and

$$d = 0.25 \text{ cm, } P = 0.63 \text{ kW.}$$

$$d = 0.50 \text{ cm, } P = 1.25 \text{ kW.}$$

which is a reduction of power to between  $\frac{1}{4}$  and  $\frac{1}{5}$  of that required for wood heating.

*Estimates of Operating Frequency*

For a typical wood whose dielectric constant  $\epsilon = 3.4$  and power factor  $\sigma = 0.055$  then for a maximum voltage gradient

$$\begin{aligned} E &= 788 \text{ r.m.s. volts per cm.} \\ &= 2000 \text{ r.m.s. volts per inch.} \end{aligned}$$

we obtain from equations (4.1a or b) that the maximum safe dissipation of power = 0.065 *f* watts per cm<sup>3</sup>.....(4.5.e)

where *f* is the frequency in Mc/s.

Equation (4.5.b) may be written in the form .....(4.5.f)

Power required per unit volume

$$= \frac{\rho c}{\zeta t} (\theta_G - \theta_A) \times 8.4 \text{ watts/cm}^3.$$

where  $\zeta$  is the ratio of glue to wood temperature, a correction inserted in the formula for wood heating alone to allow for the greater heating in the glue.

Then for  $\zeta = 2$  and the selected typical wood constants for  $t = 6$  sec,  $P = 65$  watts/cm<sup>3</sup> and  $f = 1000$  Mc/s.

and for  $t = 1$  sec.  $P = 360$  watts/cm<sup>3</sup> and  $f = 6000$  Mc/s.

If more effective concentration of heating in the glue is assumed the operating frequencies might be proportionally reduced.

*Length of System*

The length of the seam heating system required in order that a given amount of power may be dissipated in it is inversely proportional to the loss factor and to the square of the voltage gradient, where this is uniform, as when the total power is introduced gradually along the length of the system to avoid exceeding the maximum permissible voltage gradient.

In resonator systems the field intensity will always build up to the value required to dissipate all the available power, so that the minimum usable length of system will be determined by the maximum permissible voltage gradient.

In transmission systems, however, there is a maximum attainable voltage gradient at any level of transmitted power, which for low enough power levels will be less than the maximum permissible.

When all the power has been introduced into the system, the residual power and voltage decay exponentially and the length of system required to dissipate a given fraction of this residual power is dependent only on operating wavelength and power factor.

$$\text{Thus } l/\lambda_s = 0.256/\sigma \dots\dots\dots(4.5.g)$$

gives the fraction of the operating wavelength in the material over which the residual power decays to a 1/5th of its initial value.

$$\lambda_s = \lambda/\sqrt{\epsilon}$$

where  $\lambda$  = wavelength in free space.

Thus for wood with the chosen constants

if $f$ in Mc/s =	1000	5000	10,000
$\lambda$ in cm =	30	6	3
$\lambda_s$ in cm =	16.3	3.26	1.63
and $l$ in ft =	2.48	0.496	0.248

Now the relation between input power flow per unit cross-section and voltage gradient is given by

$$P = E^2 \sqrt{\epsilon}/120\pi \text{ watts/cm}^2 \dots(4.5.h)$$

which is independent of operating frequency or power factor. So that operating the chosen typical wood at the maximum permissible voltage gradient gives  $P = 3 \text{ kW/cm}^2$ .

Equation (4.5.b) may be rearranged to show

how the total power required depends on the velocity of feed and the heated cross section.\*  
 .....(4.5.i)

Total power required per unit heated cross-section

$$= \frac{\rho c U}{\zeta} (\theta_G - \theta_A) \times 8.4 \times 10^{-3} \text{ kW/cm}^2.$$

which for  $U = 60 \text{ ft/min}$ . gives  $11.7 \text{ kW/cm}^2$ .

For higher velocities of feed the residual power thus becomes a negligible proportion of the total power.

*Heating Cycle*

In order to attain the most complete polymerization of the glue for a given total heating time, it would obviously seem desirable to bring the glue up to its maximum permissible temperature as quickly as possible and to maintain it at this temperature over the whole heating cycle.

The effect of variation of intensity of heating over the heating cycle will be examined for the case where all heat generation occurs in a very thin glue line and the heat required to raise the temperature of the glue is negligible compared with that lost by conduction to the adjacent wood.

Fig. 15 shows the nature of the variation of the glue temperature both during and after the

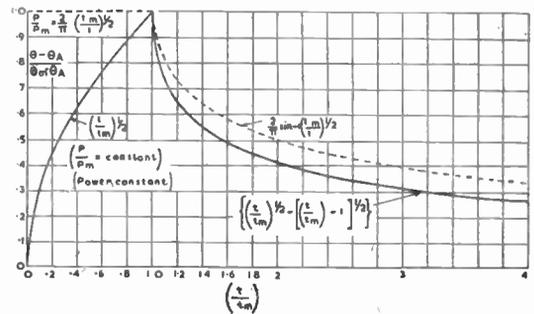


Fig. 15.—Universal Temperature-time curve. (Temperature constant)  $\theta = \text{constant}$ .

heating cycle when heat is supplied at a constant rate for a period ( $t_m$ ).

Fig. 16 shows how the power supply should

\* The loss factor and operating frequency must, of course, be such that this power can be dissipated without exceeding the maximum permissible voltage gradient.

decay in order to maintain the temperature at the maximum value attained at the end of the period of constant heat supply. The dotted curve is the limit reached when the duration of the period of constant heat supply and the time

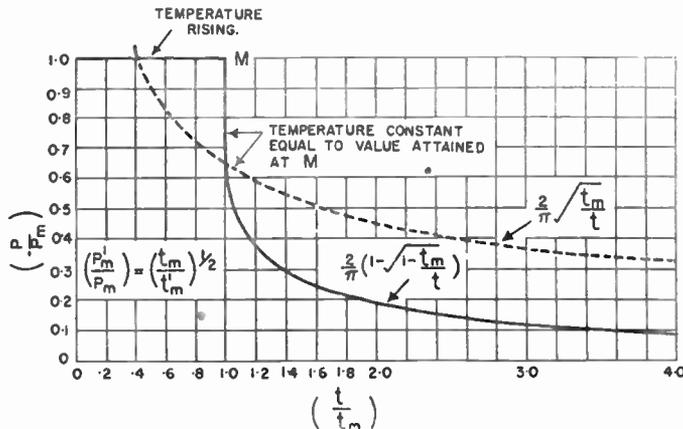


Fig. 16.—Universal power-time curves. (Power constant).

taken to reach the maximum temperature tends to zero.

The peak power required in this case tends to infinity, while the mean power required to maintain a temperature difference  $(\theta_G - \theta_A)$  in this case for a time  $(t)$  is  $(\frac{4}{\pi})$  times that required to reach the same temperature at the end of the heat period, for a constant rate of heat generation over a length of time  $(t)$ .

The most convenient method of securing this variation of intensity of heating over the heating cycle is by variation of the field intensity along the length of the heating system through which the seam is passed.

**Choice of Electrode System \***

The coaxial system of Fig. 17 permits the most effective concentration of field in the glue, the electric field passing through the glue face and wood in parallel, giving increased concentration of heating in the higher dielectric constant glue (see section (4.1.2)). Below about 10 cm the maximum permissible cross-section † of the coaxial outer conductor or the screen of

the parallel strip line becomes rather small, while above about 30 cm the minimum permissible cross-section of waveguides, unless of the re-entrant form, becomes excessively large.

In waveguide systems the field passes through the wood and the glue in series, thereby giving a less favourable concentration of power in the glue.‡ This field disposition arises because of the necessity of slitting the waveguide for insertion of the seam along a line of zero wall currents to avoid leakage of power.

For very short wavelengths, 3 cm and below, higher mode operation in waveguides might be advantageous.

Split resonator systems may be found of value for the heating of low loss high dielectric strength materials such as polythene or distrene.

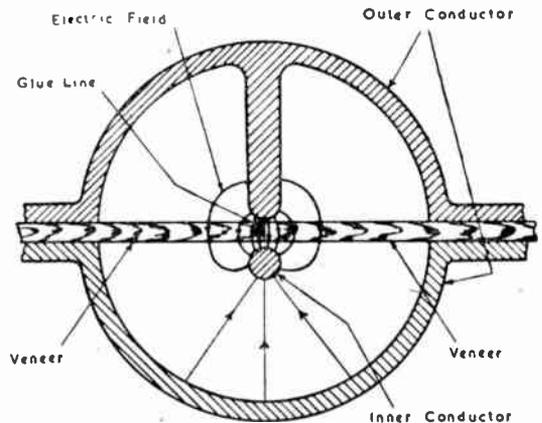


Fig. 17.—The edgewise gluing of plywood veneers. Transverse section of a "Coaxial" system.

**(4.5.4) Electro-magnetic Horn for Beam Heating**

A convenient general purpose heating system.

The arrangement shown in Fig. 18 is suitable for the wavelength range 10 to 30 cm. A rigid coaxial line feed is tapered into a flexible coaxial cable which excites the horn via a broad band probe and backing plate or a door-knob coaxial line to waveguide transformer.

‡ Except for certain higher transmission modes, such as the longitudinal section wave.

\* Provisional Patent No. 10020/47.

† For avoidance of higher modes.

For 10 cm and below the flexible link would be a flexible waveguide, needing no frequency sensitive coaxial line to guide transformation.

Above 30 cm the sizes of waveguides and horns become excessive compared with the normal sizes of loads.

An application for this system would be the rapid gluing of miscellaneous articles of

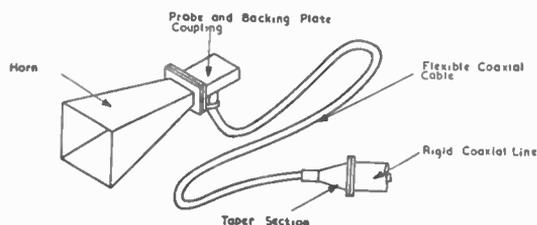


Fig. 18.—Electro-magnetic horn for beam heating.

furniture by the beamed high frequency energy, or any similar job where the numbers would not justify the making up of special electrodes.

By means of a reflector, a dielectric lens, a metal loaded dielectric lens, the beam may be made to converge to a minimum diameter of about half a wavelength. Thus, concentrated heating may be secured in internal portions of a load inaccessible for the application of electrodes.

A given area of load may be heated by parallel, convergent or divergent beams, from horns of varying mouth area at varying distances from the load surface.

The maximum proportion of reflected energy will enter the horn and travel back towards the generator, to cause mismatch in the case of the parallel beam. Reflections from a plane load surface may be prevented from reaching the generator by tilting the surface. By allowing the waves to strike the surface obliquely in this manner the amount of energy lost by reflection will of course be increased. The necessary obliquity of the reflected waves to miss the horn mouth may be minimized by increasing the distance between the horn and the load surface. Surface reflections might be minimized by the well-known device of the quarter-wave matching plate, made from low loss dielectric. These arrangements are shown in Fig. 19.

Adjustment of the probe and backing plate feed to the horn may also be used to balance load reflections. Reflections from the horn mouth

into free space become negligible when the mouth area is increased beyond a wavelength square.

(4.5.5) Food Heating

From the dielectric point of view the

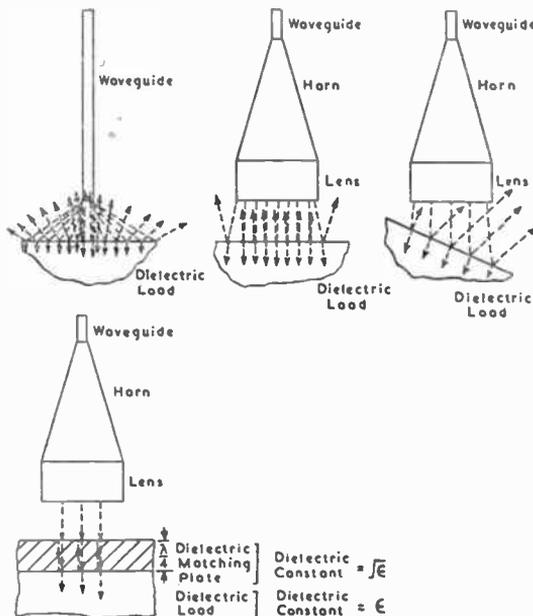


Fig. 19.—Reflections with beam heating.

collection of foods comprising a typical meal is a dielectric load of low dielectric strength, and very variable dielectric constant and power factor.

It is believed that the most uniform heating may be secured at frequencies between 3000 Mc/s and 1000 Mc/s, owing to frequency variations of dielectric properties. At higher frequencies, the depth of penetration of the high frequency energy into the food is too small, while at lower frequencies dielectric breakdown limits the rate at which power may be supplied.

At 3000 Mc/s good uniformity of heating and matching with various combinations of food has been secured by the use of beamed radiation, along the lines of Fig. 18 and Fig. 19. Reflectors are used to direct the energy onto the food from all sides, to offset the effects of low penetration, and are arranged, as far as possible, to avoid returning towards the exciting horn energy that has not been

dissipated by several passages through the food, thus making matching more or less independent of quantity, type, or distribution of food on the plate. For screening the whole may be enclosed in a metal case with a metal gauze door through which the cooking may be observed. The door may be inter-locked to switch off the high frequency power when operated. The appearance of the whole may be similar to that of a conventional oven.

Where cooking in some quantity requires to be done, the problem of non-uniformity of heating might be tackled by heating together only those foods whose dielectric heating properties are similar.

At the lower frequencies, around 1000 Mc/s

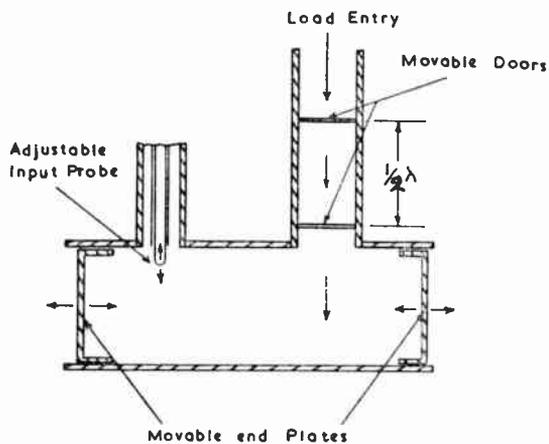


Fig. 20.—Low mode resonator.

effective concentration of power demands the use of a resonator system such as is shown in Fig. 20.

Since cooking is an operation requiring time to complete the chemical changes in the food, to take full advantage of the rapid heating attainable by dielectric methods the food should be in a partially pre-cooked state. This pre-cooking could be done in large central kitchens with freezing for storage over long periods or during slack times in local kitchens.

By conventional hot oven methods thawing and heating times are estimated to be about 15 minutes, whereas by ultra high frequency heating little over a minute is required.

The increase of dielectric constant and power factor when frozen food melts tends to cause run

away heating of those parts which melt first.

Where non-uniformity of generation of heat cannot be sufficiently reduced the length of the heating cycle must be increased to allow time for adequate redistribution of heat by thermal processes.

Cooking operations which require the formation of a crust, such as baking bread or cakes, cannot be satisfactorily performed by the dielectric heating methods already mentioned. The necessary extra heating of the surface may be secured by adjacent slabs of higher loss dielectric material which attain a much higher temperature than the bulk of the food,\* or by auxiliary radiant heating of the surfaces.

It is not always easy to determine when the food is adequately heated. One method used in practice is to make the energy supplied proportional to the weight of the food.

The generation of appreciable quantities of steam might also be used as an indication of temperature attained.

#### (4.5.6) Small Size Cavity Resonator

In order to secure uniformity of heating with a cavity of small size the dielectric load when placed at the field maximum must be in a reasonably uniform field. Its maximum permissible linear dimensions are thus limited to about one-tenth of the operating wavelength. A wavelength of 30 cm (1000 Mc/s) is thus about the minimum at which loads of useful size may be heated with a minimum size resonator.

Fig. 20 shows a typical resonator, which is made double the minimum size in order to separate the input probe from the load.† The minimum size resonator has the lowest Q-factor and least critical tuning, because Q-factor is proportional to the ratio of energy stored to energy dissipated per cycle (to make the larger size resonator Q-factor the same as that of the minimum size, identical loads would have to be placed at all the maxima of the larger resonator).

Of note is the method illustrated for getting the load into and out of the cavity, without switching off the generator. The inlet tunnel may be narrow enough to act as a waveguide

\* British Patent 599,634.

† To avoid unnecessary disturbance of matching by the load and the production of local field concentrations and overheating in the load by the proximity of the probe.

below the cut-off frequency, and long enough to attenuate adequately the high frequency energy, or be closed by two metal doors placed a half wavelength apart. Either door may thus be opened without causing leakage or disturbance of the operating conditions of the cavity, and thus the load may be introduced or removed from the cavity by first moving it between the two doors.

Tuning of the cavity is effected primarily by moving the end remote from the input probe, while matching at the probe end is by adjustment of the length of probe and the adjacent end of the cavity.

*(4.5.7) Vaporization of Liquids in a Coaxial Line\**

One application is the production of powder from finely atomised colloids. Normally this is done by drying the carrier liquid by hot air. The heating of the drops of liquid up to boiling point and the production of the requisite vaporising heat by supplying hot air has, however, the following disadvantages. On the one hand, relatively high temperatures of the supplied hot air are required, which may have a detrimental effect on the quality of the final product; for instance, destruction of albumen, vitamins, aromatic and other heat-sensitive substances. On the other hand, greater dimensions of the drying chamber are required to ensure that the descending drops shall be in the stream of hot air for a sufficiently long time.

Drying in a vacuum, in order to reduce the boiling temperature, is rendered impossible in practice by the continuous supply of hot air in quantity. Drying by hot air has the added disadvantage that the surface of the drops of liquid dries first, and the skin thus formed greatly hinders the further supply of heat by conduction.

These disadvantages are absent in the dielectric heating methods.

In the arrangement shown in Fig. 21 the liquid which has been atomized by the annular nozzle, and may have been previously concentrated, enters a conical chamber formed by the perforated outer and the inner conductors of the coaxial line. During the whole of their descent the falling drops thus remain exposed to the high frequency field and are heated through-

out their volume by dielectric losses. The whole is contained in a vacuum tight chamber connected to a vacuum pump. By the use of the cooling device, the heat of vaporization may be recovered, and, if desired, utilized for the concentration of the liquid before its atomization, and in addition, the pressure in the vacuum chamber, determined by the vapour pressure of the liquid condensing on the cooling device, is additionally controlled by a suitable choice of the temperature of the cooling liquid in the cooling device without the suction performance of the pump having to be varied.

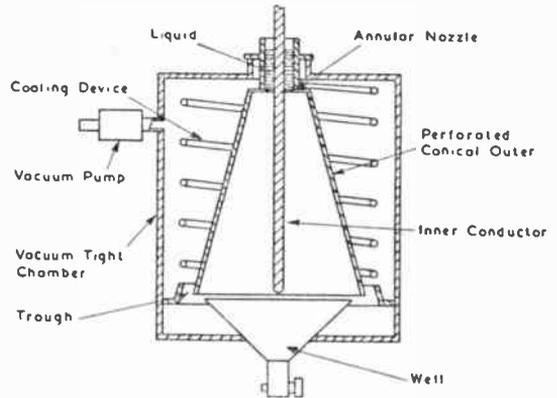


Fig. 21.—Vaporization of liquids in coaxial line.

Through the optional selection of the degree of vacuum thus made possible, a vaporizing temperature may be ensured which lies lower than any critical temperature liable to have a detrimental effect on the quality of the final product. The condensate forming on the cooling device is caught in the trough separated from the dry substance collecting in the well.

If the outer electrode is divided into separate independent sections of a cylinder, to which different voltages or frequencies are applied, additional control over the vaporization process is secured. In particular, by adjusting the applied frequencies to resonance frequencies of the molecules which it is desired to vaporize a sequence in the separation of different liquid constituents (fractional distillation) may be secured.

Further control over the heating process may be secured by the introduction of gases of various dielectric constants into the chamber.

\* British Patent 606165.

*(4.5.8) Miscellaneous Techniques.**Heating of Thin Dielectric Films\**

If the electrodes of a heating system are placed on opposite sides of a thin dielectric film the electric stress in the film, and hence the rate of heating, is limited to a low value by breakdown of the unavoidable air gap. See Section (4.1.2).

In order to obtain the maximum electric stress in the dielectric film for a given total power, flowing or stored, the spacing between the electrodes must be as close as possible to minimize the air gap, giving an inconveniently low impedance system for coupling power.

By the use of fringe field heating† the electric field may be made to spread in air giving a lower electric stress in air, to concentrate in the dielectric film giving a higher electric stress there, and to travel through a considerable length of dielectric film, thus giving a high impedance.

These features are illustrated in Fig. 22.

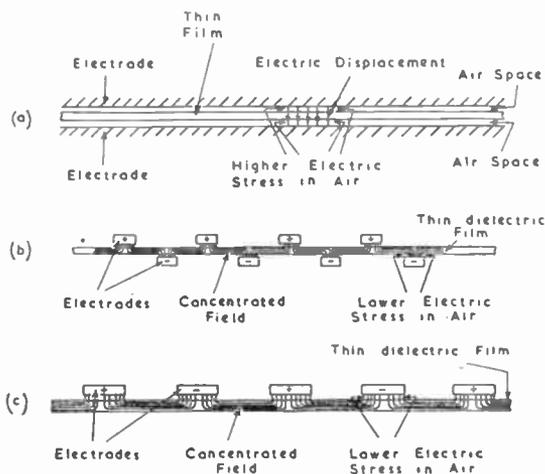


Fig. 22.—Heating of thin films.

(a) Electric field through film thickness. (b) Longitudinal electric field with electrodes on opposite sides. (c) Longitudinal electric field with electrodes on same sides (fringe field).

*Controlled Non-Uniformity of Heating.‡*

By rotation or other selected motions in a selected localized or otherwise non-uniform

\* Provisional Patent No. 36334/46.

† Reference (5.12).

‡ British Patent 599193.

field useful temperature distributions may be secured.

Fig. 23 illustrates how concentrations of heating towards the surface or the centre of a dielectric load be secured.

*Waveguide Heating of Thread or Strip Material*

Fig. 24 shows a waveguide slit along the centre of its wide face and folded back on itself several times so that the slits are in line. Thread or strip material passed through the slits will thus lie along the lines of electric force, the most favourable position. Energy propagated down the guide will thus be continuously attenuated but the average heating of each thread will be approximately equal. By using a sufficient length of guide no significant proportion of energy need be left at the end, so that matching will then be independent of change of load, only the active length of guide changing.

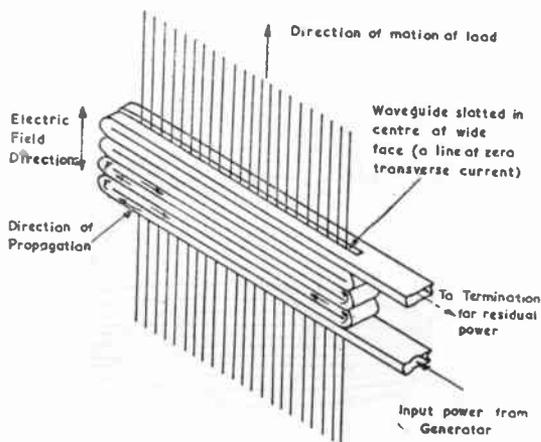


Fig. 24.—Waveguide heating of thread or strip material.

*Uniform Heating of Strip Material in a Cavity Resonator*

Fig. 25 shows strip material passing through a resonator at an angle to secure uniform heating. Slots are used in the centre of the wide face, where no main current is interrupted and small radiation occurs for narrow slot widths, the disposition also ensuring longitudinal passage of the electric field through the strip. The field strength is uniform at a maximum value for a given cross-section along a line through the slots, and varies sinusoidally with a wavelength  $\lambda$  along the length of the resonator. By making the angle of motion of the strip such that any

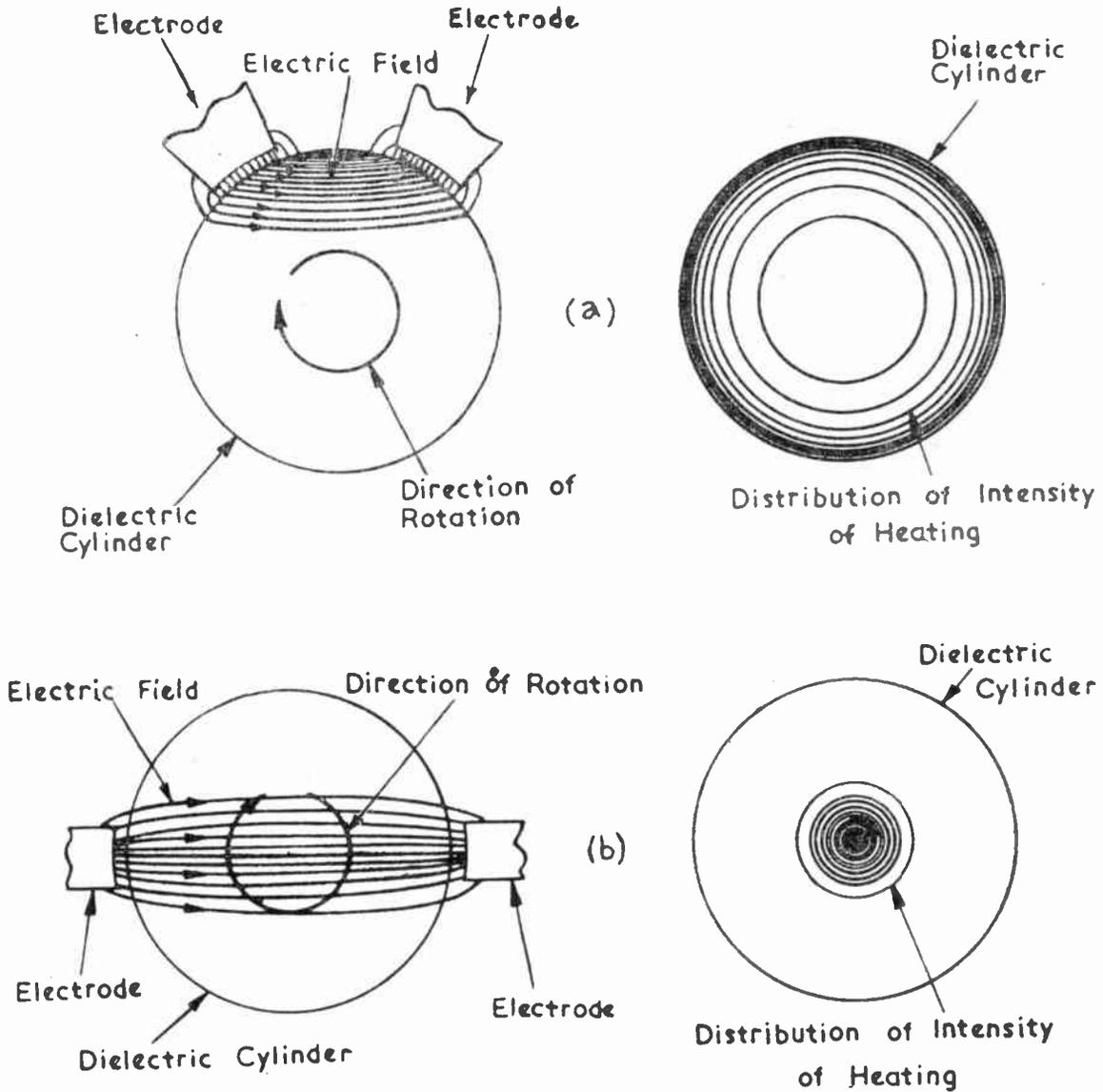


Fig. 23.—Controlled non-uniform heating.

point on it moves  $\frac{1}{2}\lambda$  longitudinally as it passes through the narrow dimension of the resonator, every point will be subjected to the same complete sinusoidal variation of electric stress and heating (in different order) and hence the same average heating.

*Miscellaneous Methods.*

Fig. 26 shows three useful techniques. At (a) a load, say a dielectric preform or vegetable block for dehydration, is shown contained in an associated holder which is resonant with the load in position. Such a

holder passed into a waveguide as illustrated will be excited correctly by the passage of the magnetic field through the looped ends.

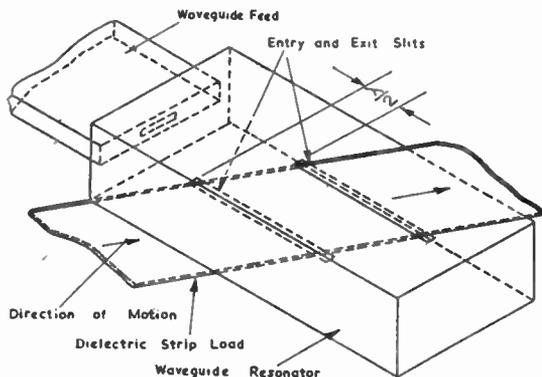


Fig. 25.—Uniform heating of strip material in cavity resonator.

At (b) the use of slits, slots and holes on the narrow face of a guide, where the main transverse current of the waveguide is interrupted, is illustrated. These openings therefore radiate strongly and may be used as antennæ or for seaming or spot welding of dielectric sheet placed against them.

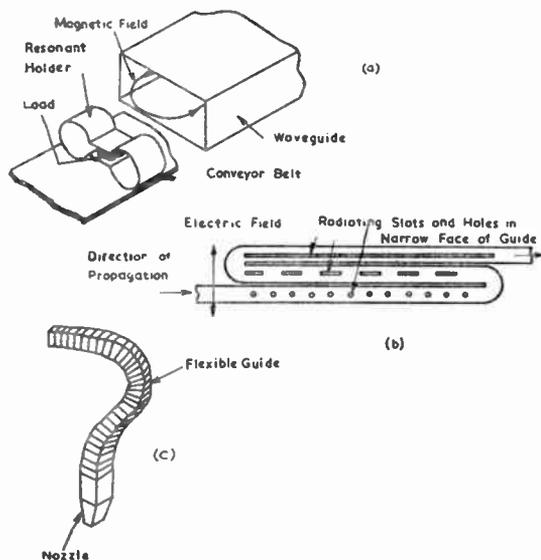


Fig. 26.—Miscellaneous methods.  
(a) Resonant load holder. (b) Radiating slots and holes.  
(c) Flexible waveguide and nozzle.

At (c) is illustrated a flexible waveguide and nozzle giving a concentrated but highly divergent

beam for heating material placed close to the nozzle.

### Acknowledgements

The author is indebted to his colleagues for help and facilities given to him in the preparation of this paper, and to Mr. L. J. Davies, Director of Research, B.T.H. Co., for permission to publish the paper.

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6. Appendix A

*Influence of Fineness of Stationary Wave Pattern on Non-Uniformity of Temperature Distribution*

When the time taken to supply the required total quantity of heat to a dielectric load is very small the final temperature distribution is proportional to the distribution of heat generation, but as this length of time is increased the non-uniformity of the final heat and temperature distribution is reduced by heat diffusion.

The time required to attain a given standard of uniformity of final temperature distribution will be greater the greater the spacing between the maxima and minima of the stationary wave pattern and less the greater the thermal diffusivity of the dielectric.

The time taken for the non-uniformity of temperature distribution after the period of heat generation to be reduced within given limits will vary similarly.

There are practical limits to the time which may be taken over a heating operation, while the adverse effect of non-uniformity of temperature distribution increases both with the degree of non-uniformity and with the time for which it persists before becoming effectively equalized.

In order to determine the order of magnitude of the wavelength for which with normal dielectrics these times become negligibly small, a single calculation under simplified conditions will be adequate.

The simplest case, that of a dielectric carrying a one-dimensional stationary wave pattern will be assumed, and the actual sinusoidal distribution of heat generation will be replaced by one in which heat generation occurs only at the maxima of the actual sinusoidal distribution.

The spacing between a maximum and a minimum which in practice varies by a factor of two or three, depending on the type of pattern and the dielectric constant of the load, will be taken as a quarter of a free space wavelength.

The simplified problem to be solved as illustrated in Fig. 27 may be stated as follows :

A portion of an infinite slab of dielectric material of thickness (*l*) equal to the spacing between a maximum and an adjacent minimum of the stationary wave pattern is considered. Initially, the whole slab is at zero temperature

when at time *t* = 0 a constant heat flux (*Q*) passes into the solid at one face, while no heat flow takes place over the other face. It is required to determine the time taken for the temperature rise of the unheated face to reach a given fraction of the temperature rise of the heated face.

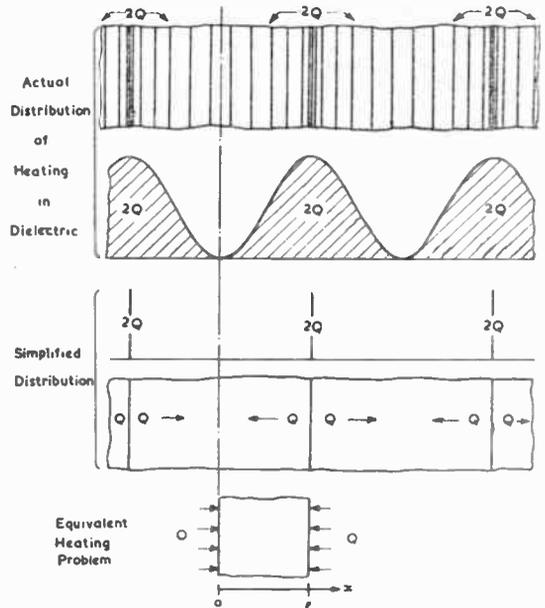


Fig. 27.—Distribution of heating with one-dimensional stationary wave pattern.

An exact solution for the temperature rise anywhere in the block, which will be simplified and adapted to the present problem, is available\*.

The solution given for the temperature rise anywhere in the block is

$$\theta = \frac{Ql}{K} \left[ \frac{R_t}{l^2} + \frac{3x^2 - l^2}{6l^2} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-kn^2\pi^2 t/l^2} \cos \frac{n\pi x}{l} \right] \dots (5a)$$

where *x* = 0 is the unheated and *x* = *l* is the heated face.

For *x* = 0 equation (5a) becomes

$$\theta_0 = \frac{Ql}{K} \left[ \frac{kt}{l^2} - \frac{1}{6} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-kn^2\pi^2 t/l^2} \right] \dots \dots \dots (5b)$$

\* Reference (5.10) p. 104.

and for  $x = l$  becomes

$$\theta = \frac{Ql}{K} \left[ \frac{kt}{l^2} + \frac{1}{3} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-kn^2\pi^2 l/l^2} \right] \dots (5c)$$

The ratio of the temperatures of the two faces at time ( $t$ ) is then

$$\frac{\theta_0}{\theta_1} = \frac{\left[ \frac{kt}{l^2} - \frac{1}{6} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-kn^2\pi^2 l/l^2} \right]}{\left[ \frac{kt}{l^2} + \frac{1}{3} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-kn^2\pi^2 l/l^2} \right]} \dots (5d)$$

As ( $t$ ) increases to infinity  $\frac{\theta_0}{\theta_1}$  increases uniformly to unity and the series terms decrease uniformly to zero.

For values of  $\frac{\theta_0}{\theta_1}$  greater than a certain value, therefore, the series terms may be neglected. To determine this value of  $\frac{\theta_0}{\theta_1}$ , the value of  $\left(\frac{kt}{l^2}\right)$  will be calculated for which the first terms of the series, and hence all subsequent terms, become negligible. Neglecting all except the first power of the first term of the series equation (5d) may be simplified

$$\frac{\theta_0}{\theta_1} = \left[ \frac{\frac{kt}{l^2} - \frac{1}{6}}{\frac{kt}{l^2} + \frac{1}{3}} \right] \left[ 1 + \frac{4}{\pi^2} e^{-\pi^2 kt/l^2} \right] \dots (5e)$$

The series term may be considered negligible.

$$\text{if } \frac{4}{\pi^2} e^{-\pi^2 kt/l^2} < \frac{4}{\pi^2} \times 0.01 < .406 \text{ per cent.}$$

$$\text{i.e. if } \frac{kt}{l^2} > 0.467.$$

For this value of  $\left(\frac{kt}{l^2}\right)$  equations (5d) and (5e) simplify to

$$\frac{\theta_0}{\theta_1} = \frac{\frac{kt}{l^2} - \frac{1}{6}}{\frac{kt}{l^2} + \frac{1}{3}} \dots (5f)$$

substituting in equation (5f) we obtain for  $\left(\frac{kt}{l^2}\right) > 0.467 \frac{\theta_0}{\theta_1} > 0.375$ . As this ratio of minimum to maximum temperatures at the end of the heating period is smaller than may normally be tolerated, the simplified equation (5f) may be used for the temperature ratios.

Let  $\frac{\theta_0}{\theta_1} = \frac{1}{2}$  be the minimum permissible temperature ratio then from equation (5f) we obtain  $\frac{kt}{l^2} = \frac{2}{3} \dots (5g)$

Typical values for the thermal constants of a dielectric load (wood) are

$$\rho = 0.8 \text{ gm cm}^{-3}$$

$$c = 0.57$$

$$K = 0.5 \times 10^{-3} \text{ Calories/sec cm}^2 \text{ } ^\circ\text{C/cm}$$

$$\text{giving } k = \frac{K}{\rho c} = \frac{0.5 \times 10^{-3}}{0.8 \times 0.57}$$

Then for  $\frac{\theta_0}{\theta_1} = \frac{1}{2}$  substituting in equation (5g) we obtain  $\frac{t}{l^2} = 608. \dots (5h)$

Let  $l = \frac{\lambda}{4}$  then from equation (5h) we obtain for

$\lambda = 0.04 \text{ cm}$	$t = 0.061 \text{ sec.}$
$= 0.40 \text{ cm}$	$= 6.1 \text{ secs.}$
$= 1.00 \text{ cm}$	$= 38 \text{ secs.}$

As  $\lambda$  increased from 0.04cm the time ( $t$ ) rapidly increases to a significant value.

It is of interest to note therefore that stationary wave patterns may not, in general, be ignored over the radio range, the limiting wavelength being of the same order as the accepted common limit of radio and infra red waves.

## TRANSFERS AND ELECTIONS TO MEMBERSHIP

Subsequent to the publication of the list of elections to membership which appeared in the January issue of the Journal, a further meeting of the Membership Committee was held on January 26th, 1949. Thirteen proposals for direct election to Graduate or higher grade of membership were considered, and seventeen proposals for transfer to Graduate or higher grade of membership.

The following list of elections and transfers were approved by the General Council : Eleven for direct election to Graduate or higher grade of membership, and eleven for transfer to Graduate or higher grade of membership :—

### *Direct Election to Full Member*

BATTISON, John Henry      New York,  
U.S.A.

### *Direct Election to Associate Member*

CHARY, S. L. V., M.Sc.      Masulipatam,  
South India  
COLLINS, Cyril, Major      Kenya  
MORLEY, Neville      Watlington,  
Norfolk  
PAYNTER, Douglas Arnold      London, E.7  
SAUNDERS, Thomas Alfred,      Glasgow  
B.Sc.  
TILLYARD, Reginald      Dartmouth  
TOCHER, John      Dunning,  
Perthshire  
WONG, Morgan Hon, B.Sc.      Hong Kong

### *Direct Election to Associate*

COOK, Dennis John      Gillingham,  
Kent  
\*GWYNN, Norman Thomas      Croydon,  
Surrey  
HAMPSON, Harry      Peru, S. America  
\*RAO, Sattiraju Sambasiva      Bombay  
ROWLAND, Norman Spencer      Orpington, Kent  
WILSON, Michael Norbury      Manchester

### *Direct Election to Graduate*

ANSTEY, Harold George      London, N.16  
GRIMM, Frank      Aberdare, Glam  
LOCKLEY, Noel Arthur      Bridgnorth,  
Salop  
TREW, Arthur Sidney      London, N.W.1

VIALLS, Arthur Frank      Exeter  
Costellow, B.Sc.  
YOUNG, John Robert,      Tenterden, Kent  
Lieut.(L) R.N., B.A.(Oxon)

*Transfer from Associate-Member to Full Member*  
BOVILL, Charles Barton      Morden, Surrey

### *Transfer from Associate to Associate Member*

BAILEY, Arthur Joseph      Epsom, Surrey  
George, Lieut.  
CHOPRA, Kuldip Singh.,      New Delhi  
B.A., Flt./Lt.  
COUSINS, Leslie William      Ilminster,  
James, Flt./Lt.      Somerset  
SAHAI, Shri Pati, B.Sc.      Allahabad,  
India  
STEPHENSON, Raymond      Saffron Walden,  
Harrison, Flt./Lt.      Essex  
WYMER, Peter Osborn, B.Sc.      Kew Gardens,  
Surrey

### *Transfer from Student to Associate Member*

AGUILAR, Esmond Charles      Hook, Surrey  
THOMASSON, Donald William      Exeter

### *Transfer from Graduate to Associate*

NORMAN, Geoffrey Percy      Epsom, Surrey  
Frederick

### *Transfer from Student to Associate*

CADOGAN, Alexander Joseph      London, S.W.11  
POWELL, Arthur Richard      Doncaster

### *Transfer from Student to Graduate*

De BEER, Baron Christian      London, N.W.1

\* Reinstatement.

The above lists also include some of the elections confirmed on 22nd February, 1949.

## STUDENTSHIP REGISTRATIONS

In addition to the list of Studentship Registrations published in the February issue of the Journal, the following fifty-two Studentship proposals were dealt with at the meetings of the Membership Committee held on January 26th, and February 22nd, 1949, these have now been approved by Council :—

AGORAM, S., B.Sc.	Kumbakonam, India	JARMAN, Eric	Warrington
AKHTAR, M. Saeed, B.A. (Hons.)	Lahore, Pakistan	JONES, Evan Haydn	London, W.12
BAIN, Wilfred Alec Peter	Enfield, Middlesex	KATHURIA, Mohindar Singh, B.A.	New Delhi
BAJAJ, Purushottam Lal	Bombay	LE VAVASSEUR-DIT-DURELL, Martin Geoffrey	Jersey, C.I.
BECKLEY, Norman James	Wembley, Middlesex	MANGOU, Aphrodit	Athens, Greece
BHATNAGAR, Brijnandan Saroop	Lucknow, India	MARLES, Ray James	Cardiff
BONNETT, James Harold	Royston, Herts	MARSHALL, Kenneth Charles	Radcliffe, Lancs
BROOKS, William Gilbert Ernest	Woodingdean, Sussex	MARTIN, Michael Blackmore	London, W.4
BROWNING, Michael John	New Donning- ton, Salop	MASTER, Kershasp Framroz	Rajkot, India
BURLEY, Thomas	Rotorua, New Zealand	MIDGLEY, Edward	Scarborough
BURRILL, Kenneth Arthur	Harrow, Middlesex	MORRIS, Charles William George	London, S.E.16
BYRNE, Michael	Cleator Moor, Cumberland	MURTHY, N. Srinivasa, B.Sc.	Madras
CAKEBREAD, John Robert Gordon, Flt./Lt., D.F.C.	London, W.13	NATH, Bhasin Rajinder	Jubbulpore, India
CHAMBERS, Albert Edward	Singapore	NICHOLLS, Jack	Welling, Kent
CHANG, Choon Ye	Sumatra	PADMANABHAN, T. S., B.Sc.	Mylapore, Madras
EPHRAIME, Sankoorikkal	Coimbatore, Madras	RAMAMURTHY, Maganti, B.Sc.	Madras, I, India
FARRELL, Ronald Leslie	Titchfield, Hants	RANFT, Clifford Hall	Holland-on-Sea, Essex
FORBES, Frank J.	West Croydon, Surrey	ROBINSON, Gordon Stanley	Whitby, Yorks
GILL, Robert Henry Ison	Co. Cork	SABHANEY, Idandas W, F./Lt.	New Delhi, India
HARMER, John Derrick	Saltash, Cornwall	SELINGER, Cyril S.	London, N.W.6
HOLGERSEN, Tor	Southampton, Hants.	SHARP, Jack Burgess	Harrold, Beds.
HORSHINGTON, Timothy Navaratnam	Colombo, Ceylon	SINGH, Gambhir Bahadur	Nepal
JANARDHANAM, Ramaswamy, B.Sc., B.Eng.	Madras, India	SNOWSILL, Alan Harold	London, S.E.21
		STONE, Kenneth Charles John	Kingsgrove, New South Wales
		SUMATHIRATNA, Kirithipala	Ceylon
		TEWARI, Hanuman Singh	Vizianagram, India
		TOWELL, Roger Percival	E. Molesey, Surrey
		UNDERHILL, Derek Donovan	Mansfield, Notts
		WILLIAMSON, Robert	Didcot, Berks.

NOTICES

**Obituary**

It is with deep regret that the Council of the Institution records the death on January 26th of William Arnold Beatty (Member).

For the last ten years Mr. Beatty regularly attended the meetings of the Institution held in London, although he was not elected a Member until February, 1943. Apart from his frequent contributions to discussion meetings, Mr. Beatty had a large number of papers published; his last to the Institution contained proposals on Television and Broadcasting Transmission Systems (*J.Brit.I.R.E.*, March-April, 1945). In addition, Mr. Beatty held a considerable number of patents.

His first appointment in radio engineering was with the Dublin Broadcasting Station and he took up his first position in England in 1930; he had service with several companies until he was first taken ill in 1941 after a period of service with I.S.R.B. In latter years he had been in poor health and, at the time of his death at the age of 51, resided in Brighton.

**Sir Ben Lockspeiser's New Appointment**

Sir Edward Appleton, K.B.E., K.C.B., will relinquish on April 30th, 1949, his appointment as Secretary to the Committee of the Privy Council for Scientific and Industrial Research.

The King has been graciously pleased to approve the appointment of Sir Ben Lockspeiser, M.A., M.I.Mech.E., to succeed Sir Edward Appleton.

Sir Ben Lockspeiser is at present Chief Scientist at the Ministry of Supply and will take up his new appointment on May 1st, 1949.

Sir Ben Lockspeiser is already a member of the Scientific Service and has risen from the lowest grade. He is now 58 years of age and his first appointment in the Scientific Service was in 1916; more recently (1941) Sir Ben was appointed Deputy Director of Scientific Research (Armaments) with the Ministry of Aircraft Production, and in 1946 he was appointed Chief Scientist at the Ministry of Supply. In this position he was responsible for the conduct of scientific research in all fields of activity of the Ministry excepting atomic energy.

**Mr. W. N. Bruce**

The Council has congratulated William Norman Bruce (Associate Member) on his being awarded the British Empire Medal in recognition of his services on behalf of the Scottish Office in developing the applications of radio to police and other public services.

Mr. Bruce has also been promoted to the rank of Chief Inspector.

**RCEEA Chairman**

Mr. F. Stanley Mockford, commercial manager, Marconi's Wireless Telegraph Co. Ltd., has been elected Chairman of the Radio Communication and Electronic Engineering Association. Mr. V. M. Roberts, British Thomson-Houston Co. Ltd., Rugby, is the new Vice-Chairman. Mr. Mockford joined the Marconi Company nineteen years ago.

On his election Mr. Mockford stated that "for many years to come the young engineer who turns to this fascinating field for a career is not likely to be disappointed."

**Vice-Admiral J. W. S. Dorling, C.B.**

On March 2nd the Director of the Radio Industry Council, Vice-Admiral J. W. S. Dorling (Member), addressed a luncheon meeting of the Radio Industries Club of Scotland in Glasgow.

**Wireless Telegraphy Bill**

**Memorandum on Radio Interference**

A Memorandum has been prepared by the Radio Industry Council and circulated to all Members of Parliament. The purpose of the Memorandum is to state simply, in non-technical language, the causes and effects of electrical interference with radio and television services, so that those concerned with the new Wireless Telegraphy Bill may appreciate the importance of dealing with this problem now. Some indication of methods of suppression is given, and the concluding paragraph concerns the necessity for legislation in this field.

**Alteration of Meeting**

The April meeting of the Scottish Section in Edinburgh will now be held on April 12th, instead of April 13th, at 6.30 p.m.